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Long-lived lives
The role of the contextual determinants

Ana Isabel Correia Ribeiro

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Ao longo desta dissertação, colaborei activamente na definição e operacionalização das hipóteses em estudo, bem como na análise estatística dos dados e interpretação dos resultados. Fui responsável pela redacção da versão inicial de todos os manuscritos e colaborei activamente na preparação das suas versões finais.

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Abbreviations

AG: Address Georeferencing
AHI: Access to Healthcare Index
BYM: Besag, York and Mollié
CI: Confidence Interval
CrI: Credible Interval
CVD: Cardiovascular Disease
EDI: European Deprivation Index
EU: European Union
EU 15: European Union (15 countries)
EU 28: European Union (28 countries)
EU-SILC: European Union-Statistics on Income and Living Conditions
GAM: Generalized Additive Models
GIS: Geographic Information System
GPS: Global Positioning System
INLA: Integrated Nested Laplace Approximation
LE: Life Expectancy
LTPA: Leisure-time Physical Activity
MAUP: Modifiable Areal Unit Problem
MEDIx: Multivariate Environmental Deprivation Index
MET: Metabolic Equivalent
NHS: National Health Service
NUTS: Nomenclature of Territorial Units for Statistics
OECD: Organization for Economic Cooperation and Development
PA: Physical Activity
PCA: Principal Component Analysis
PM: Particulate Matter
PM_{10}: Particulate Matter up to 10 microns
RR: Relative Risk
SEM: Social-ecological Models
SES: Socioeconomic Status
WHO: World Health Organization

Abstract

Background: In high-income countries premature mortality has plateau at very low levels and the progression in life expectancy now depends to a large extent on advances in old-age survival. Thus, old-age survival is an important indicator of overall population health and development. Equally important are the indicators of healthy and active ageing, being physical activity (PA) critical for older adults' survival and quality of life. Social-ecological models emphasize the role of residential contexts in shaping PA. Inequalities in health are a top public health concern and should be monitored using high resolution data. Small area studies are essential to accomplish it. Few is known about the spatial inequalities in the distribution of old-age survival at small areas and about their relation with the contextual determinants – socioeconomic characteristics of the places, access to healthcare, or physical environment. These are wide and complex concepts that should be quantified using multivariate indexes.

Objectives: 1) develop a measure of old-age survival and analyse its spatial distribution in Europe, Portugal and Porto municipality; 2) create and validate multivariate ecological indexes of socioeconomic deprivation, physical environmental deprivation, and access to healthcare; 3) estimate the ecological association b etween the previously developed indexes and old-age survival in Europe, Portugal and Porto, analysing cross-national differences and interactions between the different determinants; and 4) evaluate the association between PA among older adults from Porto and the physical and socioeconomic characteristics of the residential context.

Methods: To analyse spatial patterns and to estimate the association between old-age survival and contextual determinants, census data from 1991 to 2011 for 18 European countries at small areas and Bayesian spatial models were used. The multivariate index of socioeconomic deprivation was drawn using census and survey-based information, which allowed us to derive an individual indicator of deprivation, based on unmet fundamental needs, the gold-standard measure upon which ecological index was defined. The access to healthcare index was generated using data from hospital and primary care centres surveys, Carta Social, and measures of geographical accessibility, and it was calculated using principal component analysis. To characterize physical environment two indexes were derived based on previously validated methods and national and Europe-wide datasets: one summarizing the quality of biogeophysical environment (air pollution, climate, greenness) and other of built environments (walkability index). For Porto, specifically, we collected information on the environmental opportunities and obstacles for PA using a Geographical Information System. Data on PA of the older adults was obtained from EPIPorto population-based cohort (1999-2003 and 2003-2005). Participants were georeferenced using different methods, whose quality was matter of study. Generalized Additive Models were used to measure the association between PA and the characteristics of the residential environment.

Results: In Europe important geographical inequalities in the distribution of old-age survival were observed: in some areas less than 30% of the 75-84 years old population reached 85-94 years of age; in others more than 50%. Socioeconomic deprivation emerged as an important determinant of those patterns. Least deprived areas registered 15 to 20% higher survivorship compared to the most deprived. However, there were substantial country-to-country differences in the magnitude of the effect of socioeconomic deprivation, being more pronounced in England, Spain and Italy, and lesser in Portugal and France. Associations were generally stronger among women. In Portugal, although we have also evaluated the role of physical environment and access to healthcare, socioeconomic deprivation was still the single most important determinant of old-age survival. The contribution of access to healthcare was smaller, and the impact of physical environment was null. In Porto, we found large contrasts within the city, which could be mostly attributed to socioeconomic characteristics. Least deprived neighbourhoods had a 30-50% higher survivorship as compared to the most deprived. Physical environmental characteristics, again, played no role in explaining spatial inequalities. It is argued that the socio-spatial patterning of health is the output of inequalities in the distribution of health-related behaviours, such as PA. We found that two attributes of the neighbourhoods influenced the frequency of leisure-time PA of older adults – distance to parks and distance to non-residential destinations – particularly among females.

Conclusions: There were important geographical differentials in the distribution old-age survival in the European territory. Socioeconomic deprivation was the main culprit of those inequalities. The effect of socioeconomic deprivation was stronger in certain countries, among females and within Porto municipality. Access to healthcare impacted old-age survival as well, but in a much lesser degree and, contrasting to what has been postulated, we did not found any link (direct or mediated) between physical environments and old-age survival. However, certain physical environmental attributes seemed to impact PA among the eldest, which in turn might affect their survival chances and quality of life.

Resumo

Introdução: Nos países de rendimento mais elevado, a mortalidade precoce estabilizou a níveis muito baixos pelo que a progressão da esperança de vida depende agora em larga medida do aumento da sobrevivência em idades avançadas. A sobrevivência em idades avançadas é portanto um importante indicador da saúde da população e de desenvolvimento. Igualmente importantes são os indicadores de envelhecimento saudável e activo, sendo a actividade física (AF) determinante para a sobrevivência e qualidade de vida dos mais velhos. Os modelos socio-ecológicos têm vindo a relevar o papel do contexto residencial na AF. As desigualdades em saúde são uma grande preocupação na saúde pública e devem ser monitorizadas usando informação de alta resolução espacial. Estudos de pequenas áreas são portanto essenciais. Pouco se sabe sobre as desigualdades espaciais na sobrevivência dos idosos em pequenas áreas e sobre a sua relação com determinantes contextuais – características socioeconómicas dos locais, acesso a serviços de saúde ou características do ambiente físico. Estes são conceitos abrangentes e complexos que devem ser quantificados usando indicadores multivariados.

Objetivos: 1) desenvolver um indicador de sobrevivência em idades avançadas e analisar a sua distribuição espacial na Europa, Portugal e no município do Porto; 2) criar e validar índices ecológicos multivariados de privação socioeconómica, privação ambiental e de acesso a serviços de saúde; 3) estimar a associação entre os índices atrás desenvolvidos e a sobrevivência em idades avançadas, na Europa, Portugal e no Porto, analisando diferenças entre países e interacções entre diferentes determinantes; e 4) avaliar a relação entre os níveis de AF dos idosos portuenses e características físicas e socioeconómicas do contexto de residência.

Métodos: Para analisar os padrões espaciais e a associação entre a sobrevivência em idades avançadas e os determinantes contextuais, usaram-se informação censitária de 1991 a 2011 de 18 países europeus para pequenas áreas e modelos Bayesianos espaciais. O índice de privação socioeconómica foi obtido usando dados censitários e informação de inquéritos, que nos permitiu gerar um indicador individual de privação baseado em necessidades fundamentais não satisfeitas, o gold-standard para a definição do indicador a nível ecológico. O índice de acesso a serviços de saúde foi desenvolvido com base em dados provenientes dos inquéritos aos hospitais e centros de saúde, Carta Social, e medidas de acessibilidade geográfica, tendo sido calculado usando análise de componentes principais. Para caracterizar o ambiente físico criaram-se dois índices ambos baseados em metodologias válidas e em dados nacionais e de âmbito europeu: um acerca da qualidade do ambiente bio-geofísico (poluição, clima, áreas verdes) e outro versando o ambiente construído (índice de pedonalidade). Especificamente para o Porto, obteve-se informação sobre oportunidades e obstáculos à AF usando um Sistema de Informação Geográfica. A informação sobre a AF dos idosos portuenses proveio da coorte de base populacional EPIPorto (1999-2003 e 2005-2008). Os participantes foram georreferenciados usando diferentes métodos, cuja qualidade foi alvo de estudo. Usaram-se modelos aditivos generalizados para estimar a associação entre a AF e as características de contexto da residência.

Resultados: Na Europa observaram-se grandes desigualdades geográficas na distribuição da sobrevivência em idades avançadas: nalgumas áreas menos de 30% dos idosos de 75-84 anos alcançaram os 85-94 anos e noutras mais de 50%. A privação socioeconómica emergiu como um importante determinante desses padrões. As áreas europeias menos desfavorecidas apresentaram níveis de sobrevivência 15 a 20% superiores aos das mais desfavorecidas. Porém, observaram-se grandes diferenças de país para país, sendo o efeito da privação socioeconómica mais pronunciado em Inglaterra, Espanha e Itália, e menos perceptível em Portugal e França. A

força da associação foi também mais forte nas mulheres. Em Portugal, especificamente, embora também se tenha avaliado o papel do ambiente físico e do acesso a serviços de saúde, a privação socioeconómica foi ainda assim o factor mais determinante para a sobrevivência dos idosos. A influência da disponibilidade de serviços de saúde foi menor e o impacto do ambiente físico nulo. Dentro do município do Porto observaram-se grandes contrastes geográficos, que grosso modo podem ser atribuídos a características socioeconómicas. As áreas menos desfavorecidas apresentaram taxas de sobrevivência 30 a 50% superiores às das áreas mais desfavorecidas. Mais uma vez, as características do ambiente físico parecem não influenciar estas desigualdades. Crê-se que os padrões socio-espaciais da saúde das populações resultem de desigualdades na distribuição dos comportamentos em saúde, nomeadamente da AF. Duas características da vizinhança dos idosos influenciaram a frequência de AF de lazer dos idosos portuenses – distâncias aos parques e aos destinos não residenciais – especialmente entre as mulheres.

Conclusões: Existem grandes diferenças geográficas na distribuição da sobrevivência em idades avançadas na Europa. A privação socioeconómica destacou-se como o grande responsável dessas desigualdades. O seu efeito parece ser mais forte nalguns países europeus, nas mulheres, e dentro do município do Porto. O acesso a serviços de saúde também teve impacto sobre a sobrevivência, mas em muito menor grau, e, contrariamente ao esperado, não se observou qualquer relação (directa ou mediada) entre o ambiente físico e a sobrevivência. No entanto, certos atributos do ambiente físico do contexto de residência influenciaram a AF dos idosos, o que por sua vez poderá influir sobre a sua expectativa e qualidade de vida.

1. Background

1.1. Chapter introduction

The first chapter presents the background to the thesis, key terms, relevant studies and theories. First, the secular trends, and divergences, in life expectancy at birth in Europe and in Portugal in particular are described. Then, the components of the secular increase in life expectancy, rectangularization and extension in old-age survival, are defined, the relative importance of the two is discussed, so that it become patent the significance of addressing old-age survival as a key indicator of population health, rather than life-expectancy at birth.

After that, the importance of analysing health inequalities is discussed, the different units of assessing health inequalities are exposed, and particular emphasis is given to the "place" as unit to monitor and tackle health inequalities. Subsequently, the current knowledge on the spatial inequalities in life expectancy and mortality in Europe and Portugal is reviewed and the existence of spatial inequalities in health later in life is also assessed.

Lastly, key determinants of old-age survival are listed and revised. Particular emphasis is given to the role of the contextual determinants in shaping the spatial inequalities of the old-age survival. Biological and behavioural determinants are reviewed as well. In particular, the role of PA in enhancing old-age survival is highlighted and the intricate relation between PA and social and physical environment is reviewed and discussed.

This review chapter allows the determination of the main research gaps and justifies the main and specific objectives of this thesis.

1.2. Population ageing

Population ageing results from the combination of low fertility and extended life expectancy (1). This unbalance in population dynamics leads to a relative decrease of the children and youth and to an increase in the share of the older population groups. Despite being a major trend worldwide, Europe is the continent most impacted by population ageing. In Europe, the proportion of old population (aged 65 years old or more[1]) is 18%, but this share will continue to grow and it is expected to reach 28% in 2060 (2). Deeper changes will occur in the proportion of the oldest old (aged 85 years old or more1), which now represent 5% of the European population, but in 2060 will become 12% (2). In Portugal, figures are even more impressive – the proportion of old population will increase from 19% (2012) to 35% (2060), a large change that can be attributed to improved survival but especially to the fall of fertility.

"Population ageing is one of humanity's greatest triumphs" (3) but it also represents the biggest societal concern of the 21st century, because it affects all societal systems – economic growth, savings, investment, consumption, pensions, migration, epidemiology and healthcare (4).

1 The demographic group of the oldest-old comprise individuals aged 85 years old and over. This definition is arguable and in certain documents and reports the group of the oldest-old include individuals aged 80 years old and over.

1.3. Life expectancy at birth

Life expectancy at birth is the most commonly used indicator to analyse mortality patterns, but, more importantly, is a summary measure of population health and development. By definition, life expectancy at birth expresses the mean number of years that a new-born is expected to live at birth if current mortality conditions continue throughout the rest of his/her life (5).

Life expectancy has been growing since 19th century at a slow and almost constant pace (Figure 1) (6). The explanations for this increase are well-known and extensively described. Improvement in public health (sanitation, hygiene, medical assistance, nutrition) and socioeconomic conditions (education, income) are by far the main contributors (7-9).

In the beginning of the 20th century the average number of years a person could live was about 45 years in western[2] European countries. In 1950 this number rose to 65 years and, in the beginning of the new millennium, life expectancy reached nearly 80 years. Today the average life expectancy at birth in European Union (EU) is 80.6 years, 77.8 among men and 83.3 among women (11). That represents an impressive gain of more than 30 years in the duration of life in just one century.

All those shifts were anticipated by Thomas Warren (1929) in his theory of the demographic transition (12) and, particularly by Abdel Omran (1971) in his theory of the epidemiological transition (8). Omran defended that all nations would necessarily pass for three stages of modernization, but the time frame when each occurs would be rather variable, depending on the nation's development level. According to Omran, in the "Age of Pestilence and Famine" mortality is extremely high and fluctuating, and life expectancy does not surpass 30 years. In the age of "Age of Receding Pandemics" there is a marked decline in infant and premature mortality due to the accelerated drop in infectious diseases mortality, and life expectancy rises steadily from 30 to 50 years. And, lastly, in the "Age of Degenerative and Man-Made Diseases" mortality continues to decline, especially at older ages, and life expectancy exceeds 50 years. Later he updated the theory by introducing a fourth stage of transition (13), called "Age of Delayed Degenerative Diseases", when life expectancy go beyond the eight decade thanks to achievements in medical treatment, mostly of cardiovascular diseases (CVD). A fifth stage, "Age of Emergent and Re-emergent Infections", was also added by Omran, characterized by the emergence and re-emergence of infectious and parasitic diseases (14). Although the theory provides a useful framework for describing mortality changes and elaborate predictions, it has been severely criticized for not foreseeing counter effects, non-linear progress and divergences, and regional differences (15).

It is very important to highlight that the increase in life expectancy was an uneven process in Europe. In the 1950s, there were strong differences in life expectancy between north-western and southern European countries, the last having considerably lower life expectancies mostly due to inferior standards of living (16). Mortality started to decline first in countries like France and Sweden, where the first signs of the epidemiological transition (decline in premature mortality) showed up as early as in the 18th century (17). In southern European countries, mortality was already in a downward trend but they only caught up Western and Northern Europe in the 1960s (16). Portugal is considered an atypical nation given that even in the 1970s its life expectancy

2 For the purpose of this thesis we have followed the United Nations classification of the World regions; Western Europe includes Austria, Belgium, France, Liechtenstein, Luxembourg, Netherlands and Switzerland; Southern Europe includes countries like Portugal, Greece, Italy, Malta, Andorra and Spain; Northern Europe includes Denmark, Iceland, UK, Ireland, Norway, Finland, Sweden, among others; and Eastern Europe includes countries like Poland, Romania, Czech Republic, Ukraine and Hungary. More details in 10. UN. Composition of macro geographical (continental) regions, geographical sub-regions, and selected economic and other groupings United Nations; 2014. Available from: http://millenniumindicators.un.org/unsd/methods/m49/m49regin.htm.

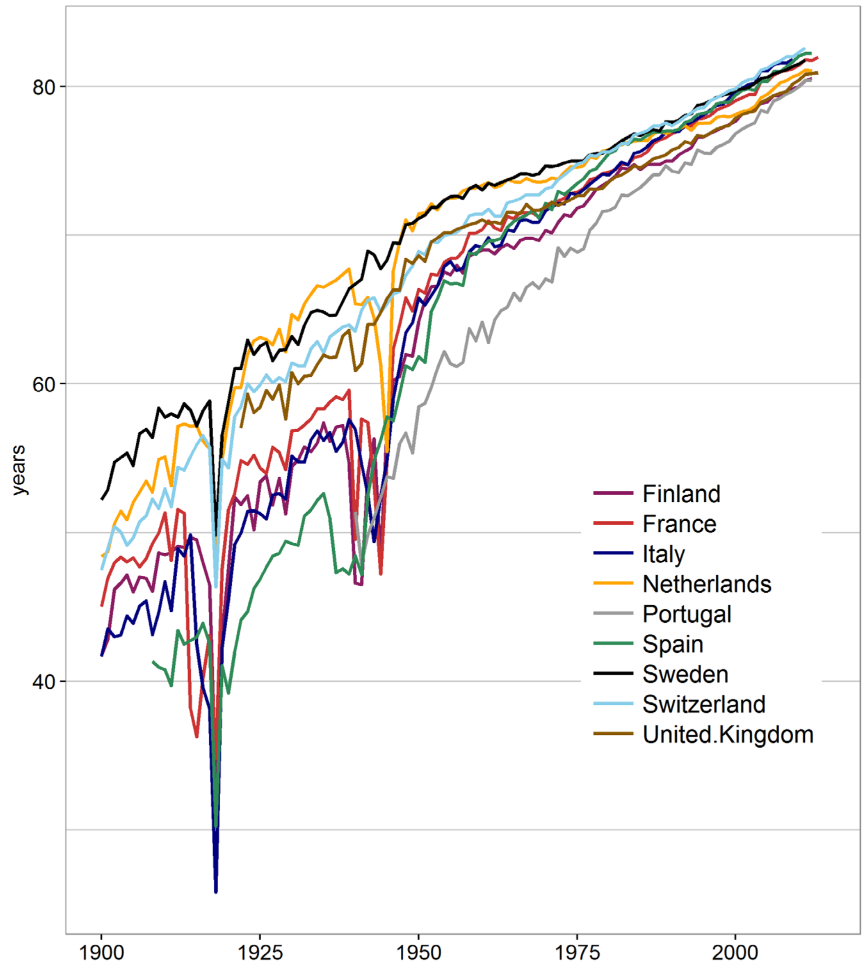

Figure 1. Secular evolution of life expectancy at birth (years) in selected European countries. (Data from the Human Mortality Database (20))

was amongst the lowest in Europe, 64 in men and 70 in women (18), but, in a matter of 30 years, Portugal caught up Northern and Western Europe, as its life expectancy rose to the European average (19).

However, countries are still not all at the same stage. After a period of convergence, in the 1970s, when the disadvantage of Southern Europe disappeared, divergence conquered Europe once again (21). Due to the health crises in the last phase of the communist regimes, life expectancy in Eastern Europe dropped, and the gap between Western and Eastern Europe became wider (16, 21). This gap has not disappeared yet. In 2013, the difference in life expectancy between European Union (EU) member states was 9 years, ranging from 83.2 years in Spain to 74.1 in Lithuania, a gap slightly larger than in the 1990s (22). Even among the core members (EU15)[3]the gap is considerable, with the life expectancy at birth ranging from 80 years in Denmark to 83 years in Spain (22).

Whether or not the life expectancy will continue to increase is still an open debate (6). Forecasts predict a steady increase in the following decades but, this upward trend should not be taken for granted; as human history has taught us, the evolution of life expectancy can be rapidly affected by political and economic circumstances, and by the increased burden of certain medical conditions (23-26).

3 Fifteen was the number of member countries prior to the accession of ten candidate countries on 1st May 2004. The EU15 comprised the following countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and the UK.

1.4. Rectangularization and extension of old-age survival

Life expectancy is regulated by two concomitant mechanisms (27-29) – the reduction of premature mortality (rectangularization of the survival curve) and the increase of maximal age at death (extension of old-age survival).

Back in the 1980s, James Fries studied the variability of the age at death in human populations, and defended that life expectancy increases but the life span is fixed (30, 31). Life expectancy across exact ages can be represented as a survival curve, with the number of survivors of a hypothetical cohort in the y-axis and the exact ages in the x-axis. A survival curve shows the number (or proportion) of individuals surviving to each age. According to Fries this curve will become gradually more rectangular, i.e. the age at death will become concentrated around certain ages. He defined rectangularization as a state in which mortality from exogenous causes is eliminated and the remaining variability in the age at death is determined solely by genetic factors. Figure 2 shows the Portuguese and Swedish survival curves; the gradual rectangularization of the survival curves is clearly observable in both countries. But, what Fries did not anticipate, was the concomitant shift of the maximal age of death towards the right of the curve, the extension of old-age survival, quite noticeable in Figure 2.

For most part of the human history, life expectancy has increased due to the mechanism explained by Fries, a reduction in premature mortality essentially caused by infectious diseases (27). But, this process of rectangularization has significantly slowed down during the last decades, with premature mortality stabilizing at very low levels (32). Since the 1970s, the increase in life expectancy is driven by the decline in mortality at old ages, that is, by an extension of old-age survival (27, 33).

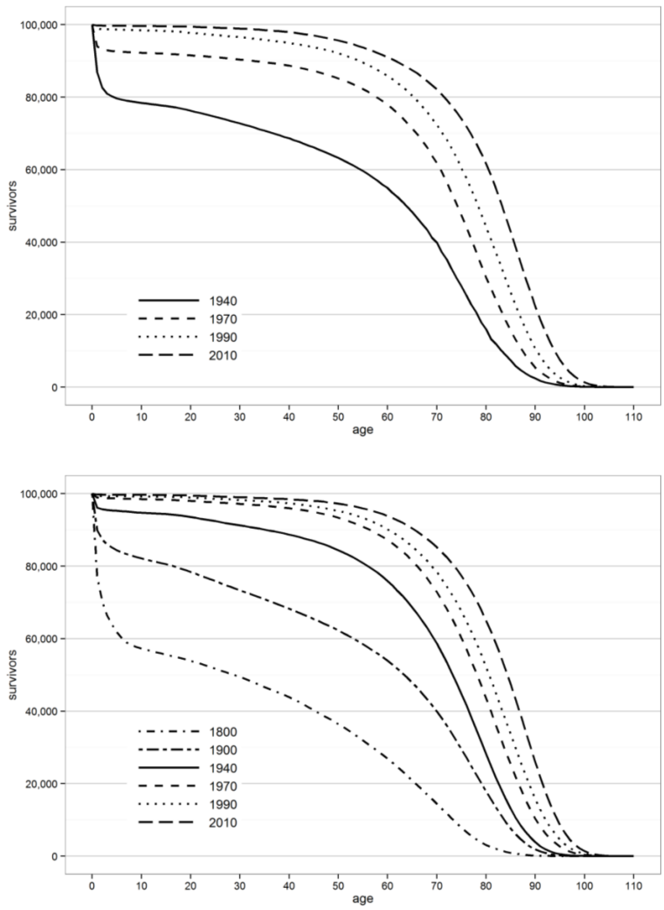

Figure 2. Secular evolution of the survival rates in Portugal (above) and Sweden (below). (Data from the Human Mortality Database (20))

As people live longer, interest shifts to the older population groups. In 2013, once a man had reached the age of 65, he could, on average, expect to live 17.9 years, with values ranging from 13.9 years (in Latvia) and 19.3 years (in France). The life expectancy of women at age 65 was higher, an average of 21.3 in 2013, ranging from 17.9 years in Bulgaria to 23.6 years in France (11). At 85 years of age life expectancy is of course considerably lower but it is gradually increasing. It is now 6.2 years among men, ranging from 4.4 in Bulgaria to 6.9 in Luxembourg; and 7.2 among women, ranging from 5.4 in Bulgaria and 8.5 in France (22).

Due to the increase in old-age survival European societies are experiencing an explosion of the oldest age groups. The group composed by people aged 85 years old and over (oldest-old) is actually the fastest growing age group in Europe. Between 2001 and 2014 their proportion rose by 41% (1.7% in 2001 to 2.4% in 2014), whereas the growing rate of those aged 65 years old or more stayed at 17% (15.8% in 2001 to 18.5% in 2014) (34). In Portugal percent increases were even greater, 60% for the oldest old age group (1.5% in 2001 to 2.4% in 2014) and 22% for the old-old age group (16.3% in 2001 to 19.9% in 2014). These trends are clearly depicted in Figure 3.

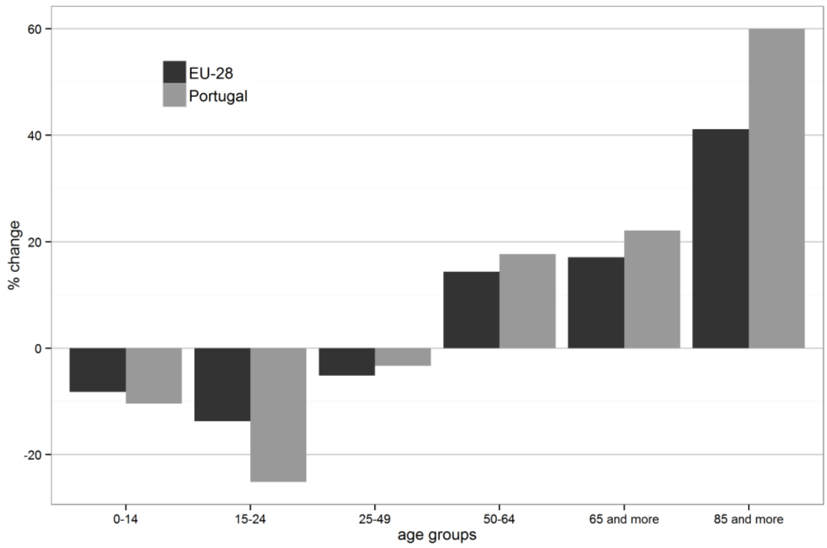

Figure 3. Percent change in the proportion of people from different age groups between 2001 and 2014. (Data from the Eurostat (34))

At the same time, the number of centenarian and supercentenarians (>110 years) is also increasing. According to the Human Mortality Database (35), the global number of centenarians in 27 European countries almost multiplied by four in only two decades: they were 15,663 in 1986 but summed a total of 57,306 in 2006. In the last of these years, the country with the greatest number of centenarians (5210) and simultaneously the highest centenarian rate was France, followed by Iceland, Spain and Italy. Portugal (with 390 centenarians in 2006) stayed precisely at half distance between the most and the least longevous European nations.

1.5. Health inequalities and the importance of the "place"

Health inequalities and health inequities

Health inequalities can be defined as "differences in health status or in the distribution of health determinants between different population groups" (36). These comprehend differences in health status between people from different geographical areas, age groups and/or social classes. Some authors prefer to use the term inequities instead of inequalities. Sometimes used interchangeably, these two terms carry unique meanings (37). All inequities are inequalities, but not all inequalities are inequities. Whenever health inequalities are caused by biological variations, free of choice, or external environmental conditions that fall outside the control of individuals, they cannot be avoided by reasonable means (e.g. the risk of death is naturally higher among older than younger) and so they cannot be considered inequities. On the other hand, when the uneven distribution of health is unnecessary and avoidable, and thus unfair, we face a health inequity (e.g. the risk of death is higher among blue-collar workers than among white-collars).

Health inequalities can be examined in different contexts; we can look at inequalities across the global population; we can look at inequalities between social groups defined based on gender, age, education, income, etc.; or we can look at inequalities between countries, regions, small areas, or neighbourhoods[4] (40). Health inequalities have been observed since at least 175 years, when the yearly vital statistics of England and Wales were inspected by William Farr (1807-1883), who detected important mortality differentials across social and economic groups (41). Health interventions to reduce health inequities are important not only to improve health outcomes among disadvantaged groups, but also for the health improvement of all population (42).

Place and space

There is a long tradition of studying health inequalities by examining how the health of populations varies in space (43, 44). But, the study of health variations across areas has been devalued by some authors who defend that the processes which operate at individual level are much more relevant to understand health inequalities (43). Truth is the processes that influence individual health might operate differently in different places (40) and studies at individual level are usually confined to very few geographical settings not allowing to detect such place-specific effects. Actually, for a long time (as ancient as the Hippocratic Oath), others have argued that place is relevant for health variation because it establishes and contains social relations and physical resources (45). Place was actually very important to medicine until the middle of the 19th century. Till then, medicine was concerned on the impact of geographic variation in air, water, or vectors on the development of the devastating infectious epidemics that affected populations at that time (44). This place-oriented view was then substituted by an individual-centred approach. This shift happened with the improvements in sanitation, that reduced infectious epidemics, and with the birth of the germ and the black box theories, which emphasized the role of single agents

4 There is not a clear cut definition of region, small area and neighbourhoods. In this thesis we were based on the following definitions. Region: "A relatively bounded area regarded as meaningful for geographic analysis by virtue of either one or more distinctive features or a high level of functional integration"38. Castree N, Kitchin R, Rogers A. A Dictionary of Human Geography: Oxford University Press; 2013.; Small area: Small areas constitute larger geographical units than neighbourhood, but smaller than regions. Neighbourhood: "refers to a geographic unit of limited size, with relative homogeneity in housing and population, as well as some level of social interaction and symbolic significance to residents." 39. Weiss L, Ompad D, Galea S, Vlahov D. Defining Neighborhood Boundaries for Urban Health Research. Am J Prev Med. 2007;32(6 Suppl):S154-S9.

(germs) and individual lifestyle (e.g. smoking, drinking, diet, and PA) in chronic diseases (46). Since the 1990s place gained importance back, especially because the dominant individual-centred biomedical orientation was proven insufficient to explain the multifactorial aetiology of the chronic and degenerative diseases, and to explain the human health-related behaviours (47).

To better comprehend the extent to which geography impacts health, it is important to distinguish between the concepts of "space" and "place". Space denotes a dimension in which biogeophysical (climate, pollution, greenness) and built features are distributed, usually geometric space, quantifiable in terms of distances. Place is the "humanized space" (48, 49). The idea of place is more specific and idiosyncratic, it is related to the belonging of a certain political or administrative unit and it also carries social meanings. These concepts are not easily discernible since they are intricately related. For instance, accessibility to resources (e.g. health facilities) and exposure to physical environmental exposures (e.g. air pollution) depends on the geographical disposition of these assets and conditions ("space"), but also on social networks and social power, interventions and regulations ("place"), which define which resources will be accessible to different members of local populations and to which physical environment conditions these populations will be exposed (45). Observed geographic health disparities are then the output of influences of space, place, or both (40).

Why look at places instead of individuals?

Looking at places instead of at individuals is then one of the possible ways of examining and comprehending health inequalities. By definition, public health refers to all organized measures (whether public or private) to prevent disease, promote health, and prolong life among the population as a whole (50). Its activities aim to provide conditions in which people can be healthy and focus on entire populations, not on individual patients or diseases. This definition clearly emphasizes the study of the populations as a whole (as opposed to medicine focused on individuals). By looking at places we answer to this requirement.

Moreover, public health measures are usually taken on a local, regional, or country basis, and to design them and to monitor their effects it is fundamental to delimitate priority areas. Non-ecological designs, such as cohort studies, are better to study aetiological causes at individual level, why someone gets ill and other don't, but they fail in comprehend differences between populations, that is, for instance, why Japanese live longer than Angolans.

As Rose stated in 1985 in his landmark publication "Sick individuals and sick populations" (51), "etiology confronts two distinct issues (…) The first seeks the causes of cases, and the second seeks the causes of incidence. "Why do some individuals have hypertension?" is a quite different question from "Why do some populations have much hypertension, whilst in others it is rare? The questions require different kinds of study, and they have different answers." The most troublesome population health inequalities rise from the causes of incidence: poverty, disadvantaged physical environments, or detrimental policies. So, ecological studies and comparisons between areas are useful to conveniently address this issue.

Rose also purposed a new strategy to promote population health. Instead of focusing on susceptible individuals and tailoring preventive strategies to them, he recommends adopting the "mass environmental control methods" to shift the entire distribution of exposure to a more favourable direction. Sanitation and vaccination in the 19th century (7, 52), motor vehicle safety in the 1970s (53), or smoke-free laws in the 21st century (54) are some of the examples of the most effective population strategies to health, all of them mass environmental control methods.

The major drawback of using areas to study health inequalities has to do with the inability to separate the so-called contextual and composition effects. Compositional explanations for health inequalities draw attention to the characteristics of the individuals (for instance, a high proportion of poor people) living in specific places. Contextual draw attention to opportunity structures in the local physical and social environment (55). In the study of the causes of health inequalities it might be useful to distinguish the burden of these two effects, although in practice it is not possible to differentiate them; the distinction between "composition" and "context" may be more apparent than real – the variables we measure in multilevel models (e.g. individual socioeconomic status, SES) might result from place characteristics (e.g. employment offer in the region) (56).

Ecological fallacy is another potential disadvantage of using geographical areas and ecological studies – associations observed at ecological level cannot at any point be transposed to individuals. Notice though that the opposite (atomist fallacy) also happens – associations observed at individual level cannot at any point be inferred to groups/areas (57). Either choosing to look at individuals or to places, tackling and understanding health inequalities is a top public health priority (58).

1.6. Spatial inequalities in life expectancy at birth and mortality

Documenting spatial differences and their development over time is an important first step in addressing underlying causes. In this section we briefly describe the present knowledge about spatial inequalities in life expectancy at birth and mortality in Europe without digging into the factors that contribute to such spatial inequalities.

As referred, life expectancy at birth and overall mortality are important summary measures of human health and development. Cross-national comparisons of the national levels of life expectancy, as the ones regularly published by the EU statistical office, are useful and interesting but hide important regional and local differences. Policies drawn based only on these broad averages will be naturally less effective. Consequently public health researchers and other stakeholders should downscale the analysis and started to look at the presence of inequalities between small areas. Small areas constitute geographical units that tend to be much more homogeneous in terms of social, economic, cultural, and environmental characteristics; they are usually limited by administrative and census-based boundaries, but other arrangements can be used. Several studies have investigated the presence of spatial inequalities in mortality and life expectancy between small areas.

The European country with the longest history of studies of this type is the United Kingdom (UK), where the existence of a north-south divide in population health has been acknowledged by numerous authors – studies showed that in the most northern districts mortality was 23% higher than in the southern ones (59). Another regional comparison reported Scottish mortality rates 15% higher than those observed in England (60). The particularly poor performance of Scotland in most health outcomes lead to the expression "Scottish effect" brought out for the first time in the 1998 to describe the incompressible[5] high mortality of the Scots (61).

As the statistical methods allowed to deal with the fluctuations associated to very small areas

5 Not fully accounted by the socioeconomic characteristics of those places.

(smoothing geographical patterns and accounting for the autocorrelation structure of the observations in space), numerous studies addressed this same question but using a much finer resolution, essential to unmask local mortality patterns and prioritize public health programs. They found that, even within England, substantial geographical variation in mortality and life expectancy exists, and observed that these high mortality locations coincide with highly urbanized and industrial areas, some of them already in a deindustrialization process (62); these areas contrast with southern England which experience low mortality rates (63). Shockingly, people in the north are five times more likely to die prematurely than those in the lower latitudes (64). This translates into important differences in life expectancy between the two regions (65). To wrap up, several studies have highlighted that the pattern of spatial variation have changed very little during the past 50 years (64) and some even claim the gap is getting larger (66-68) despite the efforts to tackle spatial inequalities in health.

But the UK is not alone in this story. In Spain, one of the European countries with the highest life expectancy at birth, a clear latitudinal pattern in mortality rates exists, with lower mortality in the intermediate latitudes (central plateau, Meseta) and the highest in the south of the country, which has a 15-50% excess mortality comparing to the national average (69, 70). In line with these findings, clusters of high mortality have been found in the southern provinces of Huelva, Seville and Cadiz (71, 72).

Likewise, France, also occupying the top rank in terms of life expectancy, exhibits important spatial differentials in mortality with little changes in the past three decades (73). As in the 1970s, higher mortality rates are observed in the North, Alsace and Brittany. Conversely, mortality was lower in Île-de-France, in the southern Rhone-Alpes and Midi-Pyrenees regions (especially for men), and, for women, in central Poitou-Charentes and Pays-de-la-Loire. More recently, Rey et al reported a similar pattern, showing a positive south-north gradient and low mortality in the Paris area (74). As in the UK, the post-industrial region of the northeast (Nord-Pas-de-Calais) exhibits particularly poor performance in terms of life expectancy and mortality.

Similar inequalities were reported in other countries. In Italy, differences between provinces in mortality and life expectancy have been observed too but without a clear latitudinal or longitudinal pattern (75). In Netherlands, it was found a high mortality region in the south and lower mortalities in the southwest and north regions (76). In Czech Republic differentials were also observed – relatively high mortality rates concentrated in north-western Bohemia and eastern Moravia and an interlaying belt of districts with low mortality levels (77).

However, very few studies have looked at Europe as a whole and the few using this approach could only look at inequalities at regional level (NUT III, Nomenclature of Territorial Units for Statistics). Richardson et al found an important gap in life expectancy at birth across European regions (nearly 10 years in women and 8 in men), which instead of getting narrower was kept constant from 1991 to 2008 (78). Similar inequalities were observable by Bonneux and colleagues which reported that the difference in life years between the 10^{th} and 90^{th} percentiles of 272 regions was 8.0 (men) and 5.6 years (women) (79).

Summing up, in several countries of Europe, spatial inequalities in mortality and life expectancy have being reported since the 1960s and despite the overall increase in life expectancy these differences seem to persist throughout time (if not increasing) and to exhibit consistent geographical patterns.

1.7. Persistence of health inequalities later in life

Several authors argue that the magnitude of the disparities later in life is rather small. They have measured the magnitude of the relative inequalities in life expectancy and mortality across age groups and found that all parameters of inequality decrease as age advances, being almost imperceptible after 85 years of age (80-82). There are reasons to expect that the relative differences in health and mortality decrease with age. Due to selective mortality, the populations that reach such advanced ages tend to be more homogeneous (81).

But, even if small, relative inequalities in mortality later in life translate into large absolute differences (83). From a public health perspective, it is crucial to combine relative and absolute measures of inequality (84). Relative inequalities tend to be larger when the health issue is infrequent, whereas absolute inequalities tend to be high when the health issue is very frequent. The largest number of deaths occurs at old ages and so any small inequality in mortality represents a source of many potentially avoidable deaths. Moreover, even if relative inequalities in older age mortality do not increase in the future, the excess deaths caused by them will certainly rise, as a result of the ageing of the population in European countries, which will accelerate in the next decades.

But, there is also evidence that the disparities in health later in life might not be as small as claimed. Huisman et al, looking at mortality patterns by SES in eleven European countries, found that, whereas relative inequalities tended to decrease with age, absolute inequalities in mortality rose exponentially with age, reaching a maximum in the ≥90 year old age group (83). Besides, even in relative terms, socioeconomic inequalities in mortality among older men and women were sometimes of similar magnitude as those among the middle aged (83). Actually it is even plausible that relative inequalities in health and mortality later in life will increase in a near future. As life expectancy progresses, even the most disadvantageous people reach advanced ages, pushing mortality inequalities in the same direction. Indeed, Engelman et al found that survivors to older ages have become increasingly heterogeneous in their mortality risks, as survival in early life improves (85).

1.8. Spatial inequalities in old-age survival and life-expectancy

Very few studies have addressed the spatial inequalities in old-age survival, mortality or life expectancy at old ages in Europe or in any part of the world. Studies on the topic are mostly within-country comparisons to identify hotspots of extreme survivorship. These studies have looked at extreme longevity (reaching ≥90 or ≥100 years old) and have tried to visually and/or statistically identify areas where the proportion of long-lived individuals is higher than expected.

The major reason for looking after places of very high longevity is the identification of clues to healthy or successful ageing (86). This exceptional group of people not only lives longer, but it also tends to enjoy good health and quality of life – life years and healthy life years approach each other (87, 88). To detect hotspots of extreme longevity across places (the so-called “blue zones”), and because using the overall population as denominators of this proportion leads to unreliable estimates, the large majority of these studies have relied on longevity indexes firstly purposed by Magnolfi et al (89), which expresses the ratio between very old and not so old population.

Using census data, Velasco (90) found spatial inequalities in the spatial distribution of centenarian population in Spain. Higher rates of centenarian population were observed in the provinces of Guadalajara, Ávila, Pontevedra, Soria, Segovia, Orense, Zamora and Salamanca, whereas the lowest rates were observed in Melilla, Granada, Ceuta, Gerona, Lerida and Albacete. Velasco conjectured that such spatial inequalities resulted from inter-provincial differences in social, cultural and environmental factors, plus from unknown genetic factors. More recently, Soriano and colleagues were intrigued by the fact that in the municipality of Es Migjorn Gran (Menorca, Spain), three male brothers survived longer than 100 years of age, one of them being considered the sixth longest living man in history (114 years old). In light of these figures, they tested whether Es Migjorn Gran presented an higher than expected number of centenarian population (91). Their hypothesis was not confirmed – apart from that family, longevism was relatively infrequent in the area of Es Migjorn Gran and surroundings.

In 2007, Magnolfi and colleagues (89) have shown there are important imbalances in the distribution of longevity in Italy. Higher ratios of individuals aged 90 years or more were found in the most economically developed areas of the country (central and northern regions) but the ratio of individuals aged 100 years and more was higher in isolated areas of southern Italy and islands, especially in Sardinia, whose particular situation was confirmed by other studies (92-95). In Continental Italy, Tuscany stands out for the high percentage of older population. In 2009, moved by previous results, Magnolfi and colleagues (96) investigated whether there were spatial inequalities in the distribution of longevous populations in this Italian region. Roli and colleagues (97) addressed a similar question in the region of Emilia Romagna, and they have found higher centenarian rates in certain provinces which persisted across time.

In Germany, Klüsener & Scholz (98) using data from 1989-2002 found hotspots of extreme longevity in north-western Germany and Berlin, a pattern that matched the life expectancy pattern in the 1900s (date the cohorts were born). These two authors did also demonstrate that the use of longevity indexes as purposed by Magnolfi et al (89) is an adequate approach to measure exceptional survival because, at least in Germany, where the distance between place of birth and place of death is rather small.

Even in Portugal, according to Amorim (99, 100), Ribeiras' parish in Pico (Azores) was "spared from the death" during a long time despite the unfavourable economic conditions: child mortality in Ribeiras was lower and life expectancy higher than in other parts of the island and of the archipelago, and old-age survivorship particularly long. These studies however addressed past scenarios (17^{th} to 20^{th} century) and no other study has looked at present figures.

Another European "blue zone" is Ikaria island in Greece, identified (101) as one of the areas of the world with higher number of longevous people, together with places such as the above mentioned Sardinia, Okinawa in Japan, Nicoya in Costa Rica (86) and Loma Linda in California.

Outside Europe, Okinawa has been highlighted by the extremely high levels of survival among the older and by the large share of centenarian and supercentenarian population (102). Lv and colleagues (103) showed that southern and north-western China have higher proportions of centenarian and nonagenarian population than the remaining areas of the country. Nevertheless, Wang et al found for the same country a contrasting east-to-west declining pattern for the space distribution of the ultra-octogenarians (104).

1.9. Determinants of spatial inequalities in old-age survival

Behind the distinct geographical patterns of life expectancy at birth and of life expectancy (and survival) at old ages, is the unequal distribution of the mortality causes at different age groups, and especially the growing importance of the CVD, as age advances, replacing external causes (more common in young people) and neoplasms (predominant in the middle ages) (Figure 4). That means that the geographical patterns of old-age survival are mostly determined by the geographical patterning of CVD mortality (97), and so spatial inequalities in old-age largely reflect the unequal distribution of the factors that contribute to that health outcome.

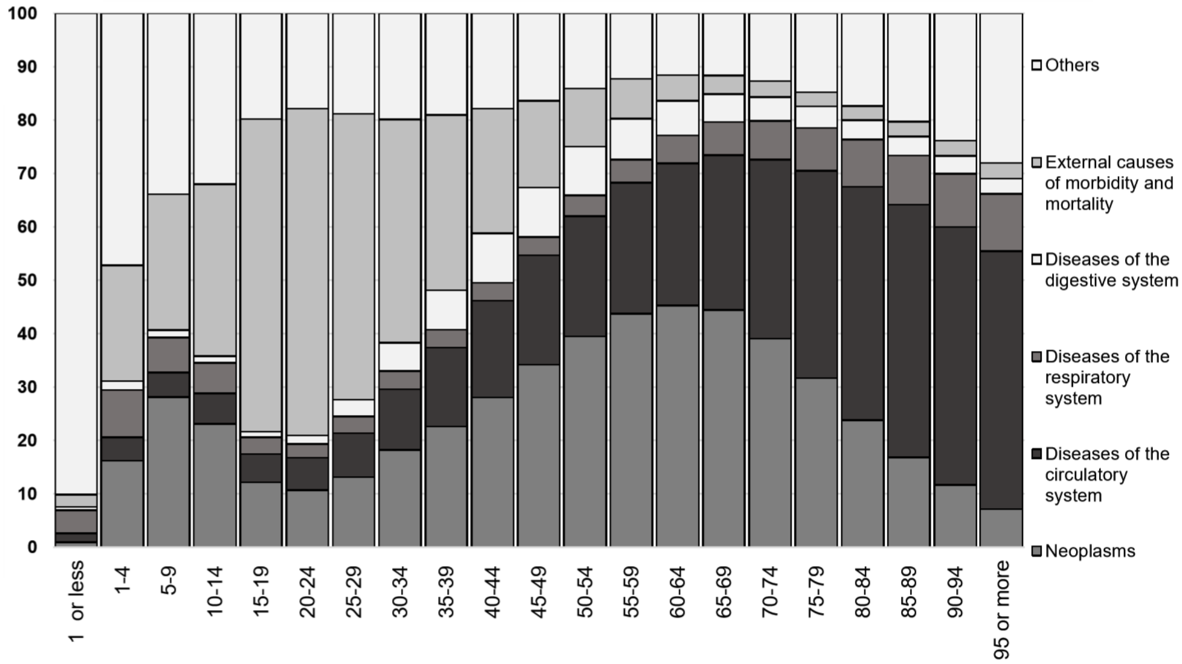

Figure 4. Causes of death across age groups in Europe (EU-28) in 2011. (Data from the Eurostat (105))

A myriad of factors can account for the spatial inequalities in old-age survival. The probability of reaching advanced ages depends on current and lifelong accumulation of exposures. These are briefly summarized in Figure 5. All types of factors, behavioural, biological, physical environment, healthcare, political, cultural and socioeconomic systems, play important roles in shaping population health along the time and they affect each other interactively; meaning that, changes in the behavioural factors might impact health systems, which, by its turn, might affect behavioural factors back.

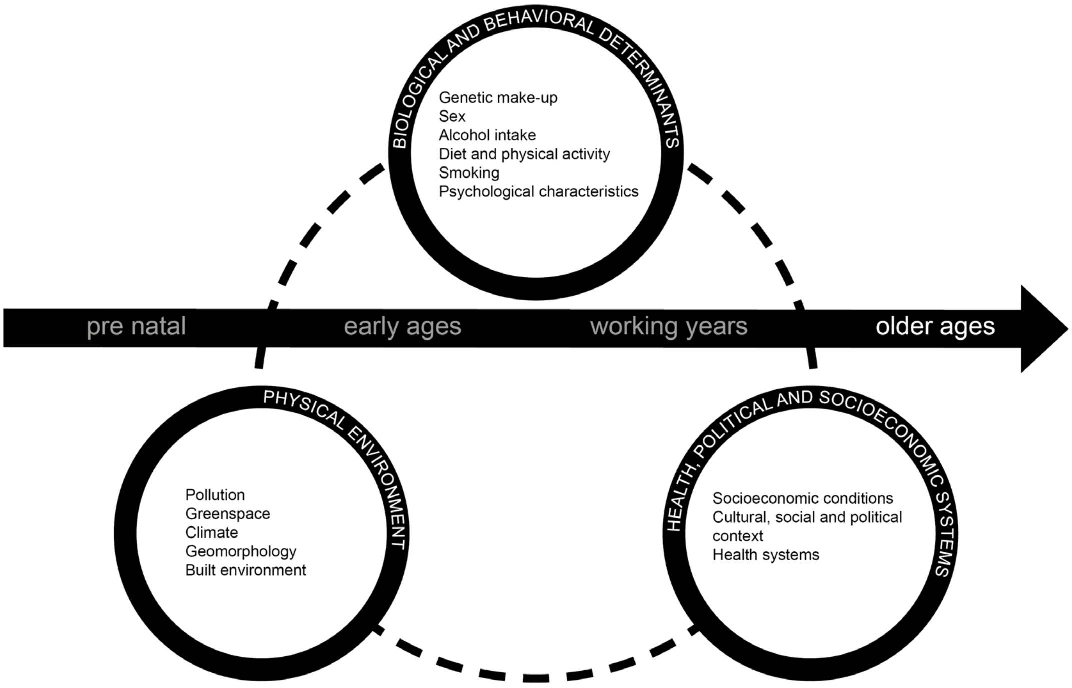

Figure 5. Overview of the possible factors implicated in the spatial distribution in old-age survival.

1.9.1. Contextual determinants

In this thesis we draw considerable more attention to the role of the contextual determinants. Contextual determinants evolve factors such as physical, health, political and socioeconomic circumstances of the places where people live. These more upstream (also called distal) determinants play an important role because they condition downstream (or proximal) determinants, such as health-related behaviours. So, they are considered the underlying causes of health, "the causes of the causes" (106). Moreover, when comparing health profiles across geographical areas, information on the population behaviours or biological risk factors is rarely available.

In this section we deliberately categorized these exposures and treated them as isolated factors but in reality these are not independent: physical environment, socioeconomic and political circumstances and healthcare system act synergistically and interactively.

1.9.1.1. Health, political and socioeconomic systems

Socioeconomic conditions

The existence of a socioeconomic gradient in health was definitely shown by the Whitehall studies of British civil servants (107), which verified that the higher the SES, the lower the morbidity and mortality. The socioeconomic gradient in health is universal, although its magnitude varies across countries and over time. Socioeconomic conditions are probably the most important factor of health and disease, it can be measured using numerous variables (income, occupational grade, educational attainment, etc.) and can be about individuals or places.

Spatial inequalities in health often reflect underlying spatial differences in socioeconomic conditions. Suffice to look at the current and past segregation of population health status across the world – poorer health status concentrated in the African countries and better health status in Europe and North America. Spatial differences in health arise from the SES of the individuals, but also from the varying degrees of exposure to contextual characteristics (presence or absence of certain features and exposures) that shape and are shaped by the personal socioeconomic characteristics.

Different mechanisms might intervene in the relationship between socioeconomic conditions and health. There are basically four theories to explain why they occur – (neo)material, cultural-behavioural, psychosocial, and life-course (108, 109). These were developed to understand socioeconomic inequalities in individual's health but they can be easily transposed to interpret socioeconomic inequalities between places.

The (neo)material model assumes that health inequalities derive from the material conditions of the individuals. These conditions are set up by wider influences that define the distribution of material conditions across population groups. The economic resources determine what individuals can afford and consequently to which characteristics of the material world they will be exposed. Lack of material resources might lead to detrimental exposures, such as poor working and housing conditions, inadequate diet, poor accessibility to healthcare facilities, residence in detrimental physical environments, etc. Material deprivation can be measured by income, by availability of amenities (car, home ownership, health insurance) and by exposure to certain environmental features. Surrogate measures such as education level and occupation can be used alternatively and/or complementary.

Material deprivation determined using household income, availability of car and home ownerships (83, 110, 111), pension earnings (112) or house value (113) was associated with mortality among older adults, and the deterioration of the material circumstances in retirement was shown to significantly increase mortality risk (114). Studies have also found that older adults with lower education levels and previously employed in manual occupations have a higher risk of dying (83, 115, 116). Huisman et al revised the evidence on the topic and found that there is convincing evidence that socioeconomic inequalities in mortality at old ages exist in the European continent (117). Some of these studies have looked at the extent to which area-deprivation (contextual) impacts mortality after accounting for the individual SES (compositional). Selective migration (i.e., the propensity of high-income areas to "attract" healthy people, the opposing happening with poorer areas) is an additional process that could reinforce socioeconomic inequalities in health (118). Studies showing that living in deprived areas is associated with increased mortality independently of the individual socioeconomic circumstances keep pilling (119, 120), which support the importance of the addressing contextual socioeconomic deprivation.

Ecological studies have been using multivariate ecological indexes of deprivation to evaluate the relation between the socioeconomic characteristics of the places and health. A dozen of studies have found a significant relation between socioeconomic circumstances of the areas and mortality and life expectancy among the older populations (74, 121, 122). Woods et al actually concluded that most spatial differentials in the UK's life expectancy at birth can be attributed to the deprivation levels of the places (65). Studies focused on the probability of surviving to extreme ages (100 or more) also highlight the importance of socioeconomic conditions (89, 123), but other investigations observed that factors such as social support, healthcare, and physical environment features, might play a bigger role (124).

The cultural-behavioural models focus on the role of health-related behaviours, such as smoking and physical inactivity, in explaining the socioeconomic gradient in health. The cultural perspective suggests these unhealthier behaviours are more culturally acceptable among lower socioeconomic groups. So, spatial differentials in the adoption of health behaviours conduce to spatial inequalities in health. The causes conductive to such behaviours are not accounted by the cultural-behavioural model, which tend to blame individuals for their own health, but current evidence showed that socioeconomic inequalities in health later in life are only moderately associated with the social stratification of risk behaviours, which seems to be highly dependent on contexts (125, 126). In the UK 75% of the socioeconomic differences in adults health were accounted by behavioural risk factors, against just 13% in France (127).

Alternatively the psychosocial theory emphasizes the feelings caused by socioeconomic inferiority. Individuals in the lower end of the social spectrum tend to be exposed to more negative life events and lack social support. These psychosocial circumstances make people more vulnerable to harmful health-related behaviours (e.g. addictions, violence) and chronic stress which initiate biological responses. The role of social support later in life is subject of discussion in the next section.

Finally, the life-course model adds a temporal dimension to the previous theoretical frameworks, and argues that health inequalities are the result of differences in material, psychosocial and behaviour factors, which influence health through time. Some studies have found that early life socioeconomic circumstances, together with the current conditions, are associated with mortality later in life (128, 129).

Summing up, regardless of the explaining theory, socioeconomic conditions are important determinants of health and therefore of mortality and survival, although the relative contributions of compositional and contextual determinants are still under dispute.

Cultural, social and political context

When evaluating between-country and within-country differences in old-age (and all ages) mortality and survival, the influence of the political, social and cultural contexts in health is critical, as important as the effects of healthcare systems, economic power and individual behaviours. If not so, strong inequalities in health status would never occur in high income countries where universal and good quality healthcare is warranted (130).

Trying to address this issue, many studies emphasize the role of the social support and social connectedness networks at older ages, not only as a complement to the formal healthcare system, but also as a protection against the adversities inherent of being ill, being poor and being alone, a situation very common among the oldest generations (124, 131-134).

One of the dimensions of the social environment that directly impacts in the social support to the elder is the relative strength of family ties. Reher studied the origin and the persistence of ancestral and deep cultural differences between the Western and the Southern European countries that have a profound imprint in the family structures, and their implications for the social cohesion and specifically in the wellbeing of the oldest (135). Comparisons between Mediterranean and Non-Mediterranean societies show that in the first old people rely more in familiar networks while in the Non-Mediterranean countries the social networks and the assistance to old people are more extended (136). Several studies showed a positive effect of strong non-kin social networks on health, but not of strong family social relations (137, 138).

The profound dichotomy between these two groups of European countries is also demonstrated by the different patterns of social connectedness at older ages, expressed in terms of non-kin relations: prevalence of formal social relations in Northern Europe and of informal relations in the Mediterranean countries (139).

The wider concept of social capital, which combines social support with dimensions like civic and political participation, sense of community and trust, is also often used, although there are many inconsistencies in its definition and measurement (140). Social capital has been positively associated with a great variety of health outcomes in studies conducted in different countries and among distinct age groups (134, 141-145). However, other studies suggest that the effect of social capital on health cannot be usefully understood if treated as a whole, not least because there is little evidence that some specific dimensions of social capital affect health outcomes like all-cause mortality (146).

Much less studied is the impact of the political systems – apart from their imprint in the typology of the national health systems – in the health outcomes. Bobak and Marmot studied the huge consequences in mortality and survival rates of another profound dichotomy, now between the former communist countries of Europe and the Western European countries (147). The authoritarian nature of the regimes that governed the Eastern Europe during decades produced generalized dissatisfaction among the citizens, frustrating their aspirations for political change, more freedom and higher standards of living; but the subsequent downfall of these regimes generated even more frustration, now caused by the loss of jobs and security and the collapse in social infrastructures. The combined effect of the two consecutive processes resulted in a dramatic increase, beginning back in the 1960s, in the prevalence of alcoholism and associated health problems, with a consequent stagnation and even decline in life expectancy, widening the gap between Eastern and Western Europe (147, 148). That geographical cleavage even led to the omission of Eastern European countries from many studies. For instance, in their recent review on the studies about the association between social capital and mortality, Choi et al excluded all studies conducted in the former Soviet Union because “it was hypothesized that the political history in that region may influence the construct of social capital in ways not directly comparable with other regions” (140).

Support to older people comes from three structures, the welfare system, the market economy and the family (149). So, recently, the welfare regime approach started to be used to comprehend country differences in health. Accordingly, welfare regimes can be grouped into types based on their shared policies, political traditions, and ideologies, which persist over time (150, 151). Different typologies have been purposed (151), but in general authors agree the more generous the welfare regimes the narrower the socioeconomic gap in health. Among older adults socioeconomic inequalities in quality of life seem narrower in equitable regimes, such as Scandinavian (also called Social Democratic), as compared to the liberal, southern European or conservative regimes (149, 152, 153).

Health systems

An health system can be defined as the combination of resources, organization, financing and management that culminate in the delivery of health services to the population (154), whose primary goal is to promote, restore, and maintain health (155). Access is an important aspect of the health systems and involves specific dimensions – availability, accessibility, accommodation, affordability and acceptability. Availability and accessibility are the two geographic dimensions of access and can be defined as the adequacy of the supply of healthcare providers and the travel time to practice locations, respectively (156). The configuration of the services is shaped by the country's economic, political and cultural circumstances.

Health systems clearly impact population health and the chance of reaching advanced ages. For instance, USA's poor performance in life expectancy, as compared to Europe, has been attributed to the bad performance of its healthcare system, in particular, to the smaller investment in the primary care sector (157). As shown in several studies and reports, the presence of a strong primary care sector seems to be critical in promoting population health and preventing disease (158, 159). The evidence also shows that primary care (in contrast to specialty care) is associated with a more equitable distribution of health in populations because it tends to be less costly and more cost-effective for the societies (158, 160).

The strength of a country's primary care system and practices has been negatively associated in 18 wealthy Organization for Economic Cooperation and Development (OECD) countries (all but three, European) with all-cause, premature all-cause and cause-specific premature mortality (161). Nevertheless, accross Europe, health policies in primary and secondary prevention are very unlike (162), with Scandinavia, the Netherlands, France, Austria and Switzerland, performing very well, whereas Eastern European countries show the worst performances; countries like Portugal, Belgium, Greece, Czech Republic and Poland had an average performance. Diversely, other studies defend that exist an inverse association between prosperity and the strength of the primary care systems: wealthier countries are associated with a weaker primary care structure and lower primary care accessibility (163). Questions of access to healthcare (namely primary healthcare) are a very important measure of healthcare quality (159). Health resources are not put randomly in space; sadly, poor areas tend to lack health resources and investment (164) so that these two detrimental factors act synergistically in shaping population health.

The quality and quantity of healthcare resources has been shown to be a critical variable in extending survival of the eldest. Evidence comes mostly from time series trying to understand the causes of discontinuities in the evolution of life expectancy at advanced ages. In Germany, after the reunification, there was an overall modernization and improvement in healthcare quality due to increased investment in the sector. This natural experiment allowed to demonstrate that increased healthcare expenditure improved mortality very rapidly, even at older ages (165). In Netherlands, between 1980s and 1990s, life expectancy after 80 years of age ceased to increase (166). But, in the 2000s, an upward trend was observable in old-age life expectancy. Among a wide range of possible explanations, the most plausible driver of such improvement in old-age survival was the expansion in healthcare for older people after 2001 (higher healthcare expenditure, more people visiting specialists, using prescribed drugs, undergoing to cardiovascular surgery, a life prolonging attitude). Mackenbach and colleagues found there was an almost perfect coincidence between the expansion of healthcare and the improvement of old-age survival (167). A recent study compared the impact of two important variables, healthcare and tobacco. Healthcare expenditure and not smoking make the most important contribution to the reversal of the trend in old-age life expectancy, which support the idea that investments in healthcare are essential in postponing mortality and for the further progress in life expectancy (168).

As consequence of the population ageing and mostly as a product of the present global economic crisis, European countries were forced to constrict their investment in health, namely in long--term care by shifting the burden of the services from the state to the families. According to some authors, this trend will much likely wide health inequalities in older population given that only those in the top of the income distribution will afford such services (169). The organization of the palliative and cancer treatment seems also to be generating health inequalities particular among the oldest (170). Older subjects (in particular those aged 85 years and more) were significantly less likely than those <65 years of age to be registered in a palliative care program, and distance to the nearest cancer centre had a major impact on registration (171, 172).

Healthcare systems are now facing important challenges caused by the emergence of the oldest-old age group, which have very specific needs in terms of healthcare. Some authors argue that the extension of survival in the older population will be accompanied by a compression in morbidity, i.e., people will live longer and healthier (31). Still, it is expected not only an increase in healthcare related costs but also in the demand for healthcare, long-term care, and palliative care services. Projections of public health expenditure on healthcare in EU from 2013 to 2060 were recently run and estimate an increase of 15% in healthcare expenditure (173). To counterbalance these effects and avoid excessive pressure over the social provision systems and healthcare systems, we need definitely to adopt the World Health Organization (WHO) active ageing approach intended to maintain good health beyond 60 through healthier lifestyles and social and civic participation (3, 4).

1.9.1.2. Physical environment

The term physical environment refers to the material features that surrounds population and includes physical (e.g. climate), chemical (e.g. pollution) and biological (e.g. greenness) agents external to the human body (5). Physical environment includes not only biogeophysical but also built features, such as parks, recreation facilities, outlets, housing and transportation. Physical environment might have a more direct impact on population health or it might promote or inhibit health related behaviours. For instance, exposure to extreme cold impacts directly the human organism, whereas built environment has a more indirect effect - it can counteract the biogeophysical exposures and also influence behaviours (diet, PA) which can be conductive to health or not.

Climate

Temperature seems to be the climatic variable with the largest impact on population's health. Older people are the most at risk from temperature-related mortality and, amongst this group, women and older people living in nursing homes seem to be even more vulnerable (174). Extreme temperatures tend to increase mortality due to a "harvesting" effect, in which deaths of the already frail and weak are anticipated. But clear spatial variations exist in the temperature-mortality relationships. Heat thresholds are usually higher in the warmer regions, and vice versa. Heat effects are particularly severe in urban areas due to the urban heat-island effect (174). The mortality-temperature association is also modified by the socioeconomic and housing conditions of the populations (175). When looking at the absolute impact of heat and cold, it seems that the most temperature-related mortality burden is attributable to cold (176).

Cross-country differences exist in the impact of extreme temperatures. For instance, in Europe, Portugal registers the highest rates of excess winter mortality, followed by Spain and Ireland (175). The lag effect of cold and warm temperatures also differs – cold effects persist longer and last for many days, while heat effects are more immediate (177). Temperature and air pollution might also act synergistically, although the presence of this effect is still under debate (178). And certain land use patterns can ameliorate the effects of extreme climatic events (179).

In a meta-analysis comprising a total of 13 million older adults deaths, a clear U-shaped relationship between daily average temperature and mortality in that age-group was observed (180). An increment of 1ºC during hot periods leads to a 2-5% increase in all-cause mortality among those aged 65 years or more, being this increase 1-2% during cold periods (180). Solely looking at the impact of heat, Åström et al found that older adult's CVD and respiratory mortality, as well as respiratory admissions, increase during hot days and heat waves (181). Studies on the geographical patterning of extreme longevity also suggest a relation with climatic variables. In China, temperature, precipitation, sunshine seem to affect the probability of reaching 100 years old (103). Average temperatures around the comfort range (20ºC), higher precipitation and relative humidity levels were associated with larger centenarian rates. Wang did also find a moderate correlation between the presence of extremely old population and temperature and the wet/dry climate (104). Similar findings were observable in Japan, where the presence of mild winters (as opposed to harsh cold winters) positively affected the probability of those aged 70 years old people reaching 100 years (182).

Geomorphology

Geomorphology refers to the characteristics of the landforms. Geomorphology conditions human settlements, climate, and population contacts. Evidence of a relationship between geomorphological characteristics and mortality is sparse, but a few studies looking at the spatial patterns of extreme longevity emphasized its role. Mountainous landforms promote population isolation and inbreeding which might lead to a clustering of life-prolonging genes among certain populations (183). Mountainous living was associated with increased centenarian rate in Sardinia (93, 95). Terrain slope was a predictor of increased survival also in Sardinia (184); these authors hypothesized that living in hilly areas is associated with higher energy expenditure due to PA. Likewise, Wang et al found that the centenarian rates were moderately associated with the geomorphological characteristics of the areas, being higher in moderate and high altitude areas (104). But the exact opposite was observed in Tuscany, where the most longevous people (≥100 years) resided predominantly in flat/urbanized areas (96).

Pollution

Pollution refers to "any undesirable modification of air, water, food by substances that are toxic or may have adverse effects on health or that are offensive even if not necessarily harmful to health" (5). Water composition has been mostly related with adverse pregnancy outcomes and infant's health, but no study has been conducted on the impact of soil/food/water contamination among the older. Contrastingly, the impact of air pollutants is well documented. Particulate matter (PM), nitrogen dioxide and ground-level ozone are recognized as the pollutants that more significantly affect population health. Their presence is ubiquitous and urban citizens are frequently exposed to higher than recommended levels of these pollutants. Regardless the population, study protocol, or region, studies have shown that these pollutants are associated with adverse health outcomes and the magnitude of these associations is particularly strong for the exposure to PM. According to WHO, 800,000 avoidable deaths occur every year due to exposure to PM, which stands as the 13th leading cause of death worldwide. As happens for climate, there is sufficient evidence to suggest that older adults (≥65 years old) are more vulnerable to air pollution-induced health effects (185). Air pollution exacerbates illness among people with respiratory disease but it also raises deaths from cardiorespiratory causes especially among the oldest.

Life-long exposure to air pollution has been associated with increased mortality among older adults. A cohort study conducted in Hong Kong reported mortality hazard ratios per 10-$\mu g/m^3$ increase in $PM_{2.5}$ of 1.14 for all causes, 1.22 for cardiovascular causes, 1.42 for ischemic heart disease, 1.24 for cerebrovascular disease, and 1.05 for respiratory causes (186). Acute effects of PM pollution are probably the best documented and these studies originated multiple meta--analyses. A recent one showed a statistically increase of 0.64% on the risk of death for older populations compared with 0.34% for younger populations per 10 $\mu g/m^3$ increase of PM_{10} (187). Among older population, women and disadvantaged seem to be the most susceptible (187). Although these studies are still embryonic, findings suggest an association between exposure to air pollution and endpoints other than death or hospitalization, namely cognitive impairment (188), diabetes (189), or depressive symptoms (190) among the eldest.

Greenspace and built environment

Greenspace is an umbrella word that refers to natural areas in the wilderness and to urban features such as parks, or gardens (191). Studies on the role of greenspace as a potential contextual determinant of health and wellbeing have multiplied in the past years but, contrasting to the effects of climate or air pollution, evidence on the salutogenic effect of greenspaces remains inconclusive.

Three pathways might help clarify the greenspace-health link – provision of PA opportunities, promotion of social contact, and the relaxing effects of nature. Greenspaces might also interact with other physical environmental aspects and act as buffers to the detrimental exposures of heat and air pollution. The lack of greenspace in the living environment is not only related to poorer health condition but is also related to people's feelings of loneliness and shortage of social support (192). Public greenspaces promote social interaction and strengthen social ties, being this impact particularly important among older adults (192, 193). Greenspace availability can also lessen the effect of stressful life events (194), and it is associated with lower cortisol levels (195), and general well-being (191). Several studies suggest that PA is the variable that bridges the relation between access to greenspace and health (196, 197). Those residing in greener areas tend to perform significantly more PA. The relations between PA and greenspace/parks are more deeply described in section 1.9.2.1. of this thesis.

Higher levels of PA, increased social capital, lower stress levels, lower levels of pollution and lesser exposure to heat might then explain the positive relation between availability of greenspace in the neighbourhood and survival among seniors, which happens independently of their age, sex, marital status, baseline functional status, and SES (198). Moreover, and interestingly, health inequalities related to income deprivation in all-cause mortality and mortality from CVD were shown to be lower in populations living in the greenest areas (199).

Related to this is the degree of urbanization/rurality of a geographical area. There are several studies (200, 201) documenting the effect ot that variable on mortality, namely in the urban areas, through the amplification the health impacts of socioeconomic and material deprivation, although the positive impact of the level of urbanization on life expectancy and all-cause and cause-specific mortality is also very well documented (74, 202, 203).

Other features of the built environment influence population health and the pathway by which this relation occurs is very similar to that linking with greenspace and health. Mixed-land uses, compactness, good aesthetics, safety, and high street connectivity are considered the key conditions to generate a healthy built environment. Settings that fulfil these requirements guarantee easy access to a wide range of daily destinations (services, recreational, cultural places, and shops, healthcare), promoting wellbeing, social interactions and walking trips (204).

The type of services and retail available in the places can also impact dietary patterns and addictions. Some food environments facilitate the access to affordable healthy food, whilst others (called obesogenic environments) facilitate the access to fast food outlets and other not so healthy food options. Although evidence is still limited, some studies have shown that good provision of healthy food in shops and restaurants is associated with lower prevalence of obesity among seniors (205, 206). On the contrary, availability of tobacco and alcohol outlets might encourage consumption and conduce to disorders associated with that use (207, 208). Studies have also showed that the spatial distribution of these retails is conditioned by socioeconomic characteristics – poorer neighbourhoods tend to exhibit unhealthier food environments and higher density of tobacco and alcohol outlets (68, 209, 210).

The same applies to housing conditions, a decisive feature of built environment. Bonnefoy (211) have summarized the role of inadequate housing, potentiating an huge variety of health threats, from bad indoor air quality, hygiene and sanitation to the promotion of home accidents or unhealthy lifestyles, not to mention its contribution to low thermal comfort, a problem of great concert among old people.

1.9.2. Biological and behavioural determinants

Gender is by far the factor that most impacts the probability of reaching advanced ages. Despite the gender differences in life expectancy and old-age survival are getting narrower, women live on average longer than men. Higher levels of oestrogen in women are considered the main contributor to the gender imbalance (212). Oestrogen protects women against CVD until menopause, whereas high testosterone levels in men puts them at higher risk of CVD and risky behaviours (violence, accidents, dependences) (213). Stresses like smoking and drinking are now more common among women, which explain some convergence of the gender's life expectancies.

Twin studies have suggested that genetics is involved in about 25% of the variation in longevity, the remaining being attributed to environmental exposures (214, 215). Information from the genotype expresses as phenotype under the influence of environment (216). Many genes have been consistently linked with old-age survival, because they play an important role in several cellular and metabolic functions linked to ageing (216, 217). Some of these genes are overrepresented in long-lived communities (102, 218). Hereditability is usually employed to measure genetic variation at population level. Studies on spatial clusters of extreme longevity found that long-lived individuals tend to have equally long-lived relatives (219), which can happen due to clustering of genetic variants affecting health and survival caused by high inbreeding. These studies have shown inbreeding rate plays an important role in shaping the geography and the sex ratios of extreme longevity (92, 183, 219). Notice however that not all familial effects are genetic (219). Family-shared behaviours and lifestyles might be more influential. And more importantly, genetic variability across regions has been shown to be small (220), meaning that spatial differentials in health are hardly due to population genetics.
Roughly 75% of the variability in life expectancy can be attributed to contextual determinants

(e.g. socioeconomic and physical environment) and behaviours, such as diet, smoking, alcohol consumption and PA, which, as we previously emphasized, are also conditioned by diverse contextual determinants. Numerous studies have looked at the effects of dietary patterns on human survival. Adherence to healthy diets, characterized by high intake of fruits and vegetables, low ingestion of saturated fats and appropriate protein consumption, was associated to increase survival among older adults (221). In Europe and USA, 10% deaths after 60 years of age can be attributed to unhealthy diet (221). A well-known example of a healthy dietary pattern is the Mediterranean diet characterized by a high consumption of fruit, vegetables, legumes, cereal, and fish and a low to moderate consumption of meat, dairy products, and alcohol, mostly as wine. Diverse studies have shown that following a Mediterranean diet positively affects survival among older adults, mostly due to the protective influence against CVD (222, 223). This type of dietary pattern is common in southern European countries, where, coincidently or not, are located many of the hotspots of extreme longevity and the national highest life expectancies.

Evidence on the negative effects of smoking is abundant. Smoking patterns have been shaping the life expectancy levels of the nations since long time (224). The lower gains in life expectancy among women as compared to men in the last decades were to a large extent caused by smoking (225). Various authors have tried to explain the evolution of old-age life expectancy in light of the smoking epidemic, but the role of tobacco epidemic at these advanced ages is rather small (226). Anyway, individual level studies have shown that is possible to remediate the effects of lifelong smoking; although those that have smoked in the past are at higher risk of death, older adults that quit smoking can expect to live a longer and healthier life after smoking cessation (227).

Of course, other determinants have been matter of study. To name a few, marital status (228), psychological aspects, such as personality traits (229), self-efficacy (230), and depression (231), have also been consistently related with survival among older adults.

To generate a comprehensive view of the determinants of old-age survival a few cohort studies have looked at the role of diverse factors on the chance of reaching advanced ages. Yates and colleagues found the probability of a 90-year life span at age 70 years was 54% in the absence of smoking, diabetes, obesity, hypertension, or sedentary lifestyle (232). Another study found that the lack of adherence to this kind of low-risk pattern was associated with a population attributable risk of 60% of all-cause deaths, 61% of CVD deaths and 60% of cancer deaths (233). Factors such as moderate alcohol use, regular PA, high education, being married, among others are also referred as correlates of old-age survival (234). Studies looking at longevous communities (Ikaria, Sardinia, and Okinawa) yielded similar results – healthy eating habits, avoidance of smoking are key determinants. In parallel, studies have also highlighted the role of less traditional factors, such as frequent socializing, mid-day naps, and pastoral living (184, 235).

1.9.2.1. Physical activity and active ageing

Definitions, health benefits and the burden of physical inactivity

Physical activity is defined as "any bodily movement produced by skeletal muscles that results in energy expenditure" (236). Physical activity should not be confused with exercise, which is a subset of PA that is planned, structured, often repetitive, and aims to improve and maintain physical fitness (236). Physical activity occurs in numerous settings, being commonly classified into four distinct domains: occupational, transport, household and leisure-time PA (237-239). Occupational PA occurs in the workplace, transportation PA includes walking and/or cycling to places mainly for utilitarian purposes, household PA involves house chores, and leisure-time PA includes exercising for recreational or health purposes, and sports. Besides, PA can be classified according to its intensity using cut-points based on metabolic equivalents (METs[6]) (240, 241). Three classes are usually defined – light (e.g. causal walking), moderate (e.g. brisk walking), and vigorous PA (e.g. running).

The WHO identifies the lack of PA as the fourth leading risk factor for mortality, accounting for 6% of deaths worldwide (242). Regular PA has numerous health benefits in any age strata, but studies suggest that the benefits are even greater later in life, when the illness and medical conditions caused by the lack of PA are more common (242). International guidelines for older adults recommend 150 min of moderate-vigorous PA per week or 75 min of vigorous-intensity PA per week, or an equivalent combination of moderate and vigorous PA (242). Physical activity is associated with increased survival among older adults (243-246) and even light intensity PA (below the international guidelines) is associated with lower risk of death. A recent meta-analysis has showed that an amount of PA below current recommendations can reduce mortality by 22% in older adults (247). Findings of this kind pile in the literature (248, 249) suggesting the benefits of PA occur in a linear fashion, with no minimum threshold. Besides regular PA is also associated with reduced cancer incidence (248), better mental health (250), improved functional and cognitive function (251, 252), reduced risk of falling (243, 253), better cardiometabolic profile (254, 255), and improved quality of life and medical outcomes in cancer patients (256-258).

Physical activity is then an essential component of active ageing. The concept of active ageing was introduced in the 1990 by the WHO, which defines active ageing as "… the process of optimizing opportunities for health, participation, and security in order to enhance quality of life as people age" (3). The WHO reinforces the importance of adopting healthy lifestyles, such as PA, at all stages of the life course – "One of the myths of ageing is that it is too late to adopt such lifestyles in the later years (…) engaging in appropriate physical activity, healthy eating, not smoking and using alcohol and medications wisely in older age can prevent disease and functional decline, extend longevity and enhance one's quality of life" (3).

Despite all this evidence, the vast majority of the population never engages in PA. In 2013, according to the Eurobarometer survey, 42% of the European adults reported never engaging in PA, a percentage that reaches 55% among those aged 55 years old or more (259). Results from this survey also reveal important cross-country differences. Portugal, for instance, occupies a top position in terms of prevalence of physical inactivity (64% of the adults), whereas the northern European counties show significantly lower levels (e.g. 14% in Finland, 9% in Sweden) (259). In 2010, data was disclosed for more disaggregated age groups and revealed that the proportion of those that never exercise increases exponentially with age and is higher in women – at 70 years of age 70% of the women (61% men) reported they never engage in PA.

Social-ecological models, neighbourhood environment and physical activity

Diverse studies have been developed to understand why some people are physically active and others don't. This knowledge is required to delineate and improve public health interventions. Because PA is typically seen as an individual-level behaviour, for a long time research on this topic focused on individual and interpersonal determinants, such as health status, education le-

6 MET (Metabolic equivalent) – The ratio of the work metabolic rate to the resting metabolic rate. One MET is defined as 1 kcal/kg/hour and is roughly equivalent to the energy cost of sitting quietly. A MET also is defined as oxygen uptake in ml/kg/min with one MET equal to the oxygen cost of sitting quietly, equivalent to 3.5 ml/kg/min. From: 240. Ainsworth BE, Haskell WL, Herrmann SD, Meckes N, Bassett DR, Jr., Tudor-Locke C, et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. Med Sci Sports Exerc. 2011;43(8):1575-81.

vel, motivation and self-efficacy. Despite being important factors (260-263), truth is individual-level interventions have been unsatisfactory (47, 264). The effect sizes of many types of individual-based PA interventions are small to moderate; recruitment rates to programs tend to be modest; and the maintenance of PA following programs is poor (265).

In the past two decades, the number and type of factors examined as correlates of PA was extended by the adoption of the social-ecological models (SEM). Social-ecological models differ from the traditional behavioural models because they recognize the importance of environment (266). Accordingly, policy, physical and social environments are important determinants of PA and interact with the individual and interpersonal factors (262, 267). The scheme from Figure 6 is one of the most widely used SEM of the determinants of PA and it clearly summarizes the multitude of factors involved.

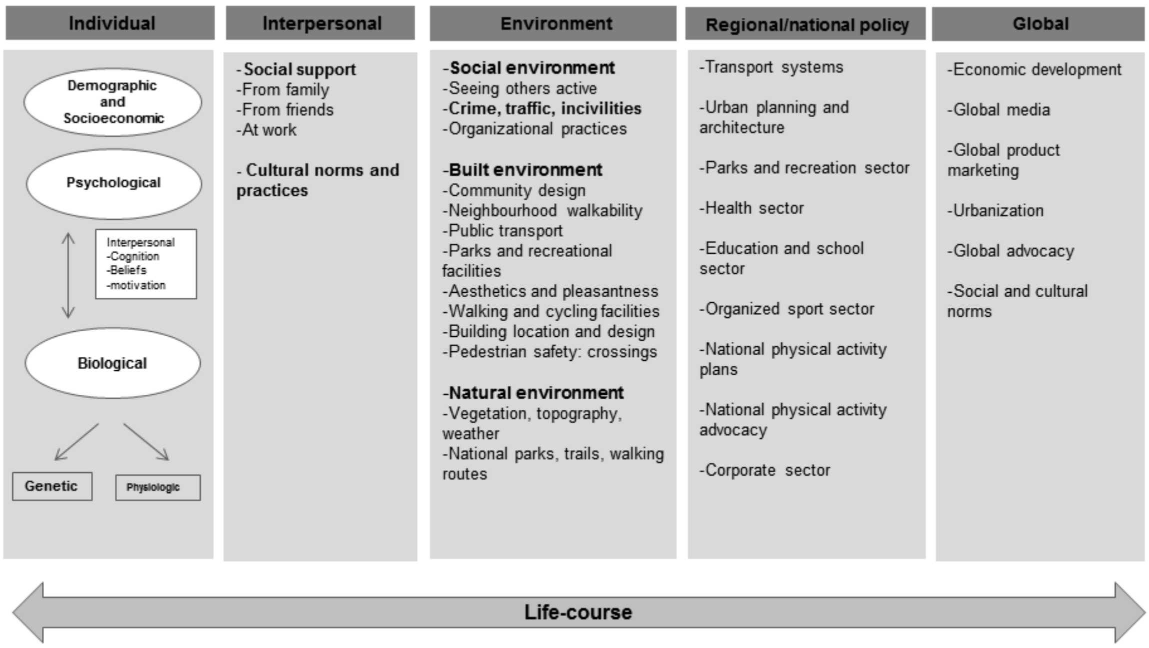

Figure 6. Social-ecological model of the determinants of physical activity. (Adapted from Bauman et al (2012) (262))

Social-ecological models valorise interactive relationships between individuals and environments, and recognize the significance of the built and social neighbourhood environments in shaping population PA levels. Built environment refers to the physical form of the urban settings and consists of three components – land-use patterns, transportation systems, and urban design characteristics (268, 269). Land-use patterns define the arrangement of activities in the city, which impacts the proximity between trip origins and destinations (268). There are essentially two variables about land-use patterns: density and mixture of uses. High density of PA-friendly equipment and mixed land-uses (residences, commerce, recreational) promote PA, and reduce the need to rely on car. The transportation systems connect places to each other. Different transportation systems include streets and roads, transit systems (e.g. bus, rail, metro), and specialized networks (e.g. bike lanes). Their arrangement influence how easy or difficult it is to get from one place to another. Certain transportation systems – well-connected street networks and good transit systems – can give pedestrians (and bicyclists) more capacity for moving about the environment without needing a car (269). Urban design characteristics describe the design and styling of the buildings, streets and other elements of the built environment, including sidewalks, street furniture (benches, lights, waste containers), crosswalks, and beautifying elements (trees, water, monuments). Urban design characteristics influence how an individual perceives the built environment (269). People decide to walk or not to walk, to visit or not to visit certain equipment, based not only on distance/accessibility aspects, but also on more intangible factors such as safety and attractiveness. The social environment includes aspects such as social cohesion and social capital, and neighbourhood deprivation (270). Heath-related behaviours, such as PA, are socially pattern meaning that social environment might support or inhibit active living.

From all age groups, older adults are probably the most affected by the characteristics of their neighbourhoods (56). As people age, they want to age in place, i.e., to live in one's own home and community safely, independently, and comfortably, regardless of age, income, or ability level (271). Moreover, due to retirement, older adults tend to spend more time in the home surroundings and have more time to enjoy the facilities in these surroundings, being much more exposed to the opportunities and harms of their neighbourhood. Older adults tend to present lower mobility and, consequently, more fear of moving outdoors (272), which might diminish their willingness to seek for PA resources far from the residence. Diminished cognitive capacity may also difficult spatial cognition and organization leading to an increased vulnerability to environmental stress (273).

Although older population have been quite disregarded from the literature on the topic, different motivators and barriers to PA in older adults have been mooted. One of the most widely study characteristics of the built environment is the presence of daily destinations in the neighbourhood. Numerous studies agree that the presence of daily destinations (e.g. shops, services, restaurants, churches) promotes leisure-time PA (204, 274), walking (275), walking for transportation (276-279), and cycling (280).

Under the assumption these facilities enhance leisure-time PA and moderate-to-vigorous PA, the role of the presence of sport and recreational facilities (trails, walking tracks) within the neighbourhood has been studied as well. Several studies reported their presence in the home surroundings is associated with more frequent walking behaviour (281), sufficient walking (277), leisure-time PA (282), sports activity (283), and higher willingness to adhere to an exercise program (284). Some of these studies have also highlighted that as important as having this facilities nearby is the quality of those facilities (237), and the cost and supervision of the exercise programs (284).

Green, open spaces in a neighbourhood such as parks and community gardens can offer older people with opportunities to engage in PA – places to walk or jog, and specific facilities for sports, exercise, and other vigorous activities (285). According to the Eurobarometer survey (286), parks are amongst the preferable places to engage in PA: 56% of the older adults reported preferring parks for being physically active; only 3% preferred sport and fitness clubs. Different studies have found that living near parks and green areas is associated with increased walking and overall PA (287-289). More recently, researchers started to test if having a park nearby is enough, or if for the park to be used it needs to fulfil certain characteristics. It seems both factors are important; park proximity and park characteristics were both related to park use and park-based PA (290, 291).

High residential density usually originates increased traffic congestion, which might make more convenient to walk or take public transportation than to drive. It is also means more people in the streets, which might induce feelings of safety and social support (292). Thus, several studies showed it is related with higher PA among elders (293, 294).

In terms of transportation systems, studies have shown that a good provision of public transport (bus, metro services) contributes to more frequent walking, meeting the PA recommendations (274), and to increased transportation PA (280). Because street connectivity shortens distances between places it might be related to increased transport-related PA. There is evidence that living in a highly connected area is positively related with walking (295, 296).

To express how supportive the neighbourhood is to pedestrian dislocation, different composite measures have been employed (297-303). The walkability index is by far the most widely used indicator, comprehending three components of the built environment (residential density, land-use mix and street connectivity) (298). Several studies found that the walkability index is positively related with walking behaviour especially for transport purposes (293, 304-307).

Urban design characteristics seem also to impact PA among the elders by making the environments more appealing and safe. The most frequently reported motivators of PA are the aesthetically attractive and quiet surroundings (308-312), the presence of well-maintained sidewalks and pavements (312-314), and the existence of rest areas and provision of safe crossings (314). Conversely, trash, noise and pollution (309, 310), and the presence of slopes and stairs (309) are associated with lower PA in older adults.

Despite much more attention have been given to the built environments, social features of the neighbourhoods seem to play an important role as well. Despite the inconsistent results in this study area (315), the presence of crime (316), perceived safety from crime and traffic (317-319) and the presence of signs of disorder and incivilities (e.g. presence of strangers, trash in the street, crumbling sidewalks) (320) appear to act as barriers to PA among senior populations. Contrastingly, high social support in the neighbourhood (321), living participatory communities (322) and seeing others exercise (287) seem to increase the odds of being physically active. Neighbourhood socioeconomic deprivation is also associated with decreased levels of PA among older adults (317).

However, these associations might be more complex than what is typically conceptualized. Modification effects have been identified throughout the literature. Usually women perceive their environment as less favourable to PA and certain features of the built environment seem to have a bigger impact on women PA levels, whereas other tend to exert larger influence in men (323, 324). Studies also reported that living in walkable neighbourhoods might be have a larger contribution to elevate PA among the most deprived people and places (311), but the opposite was also observed (275). Studies have also shown the positive impact of living in walkable neighbourhoods is only evident among elders that enjoy good social support and self-efficacy (304). Qualitative research methods might be particularly useful to untangle such interactions, since they can complement quantitative research and disclose not only what but also how and why environmental factors relate to PA (325, 326).

Most of these findings came from cross-sectional studies, which despite having numerous advantages namely in terms of sample size and diversity of variables to study, do not allow proving causal relationships. Longitudinal studies are sparse, but in general yielded similar conclusions as the cross-sectional research (327, 328). Very few intervention studies exist on the impact of neighbourhood environmental changes and PA behaviours. To date, most of the authors have taken advantage of natural experiments to measure their impact on PA behaviours. According to these few studies, interventions seem to positively impact residents' perceptions about their neighbourhood and to improve park-based PA (329-331). A randomized clinical trial was recently conducted and provided similar insights – with a modest investment it is possible to improve park-users satisfaction and park-based PA (332).

Several literature reviews have been conducted in the past few years (325, 326, 333-335). Most of these concluded that results are mixed and there is still not enough evidence to prove neighbourhood environment significantly impacts PA in older age groups. Many studies addressed a wide range of neighbourhood correlates of PA but only a few neighbourhood characteristics significantly impact PA. Most of these studies (90% in 2011), however, have been conducted in the USA and, to a lesser extent, in Western Europe, which limits the external validity of their findings (325, 333). Authors from these revisions attribute the inconsistent and mixed-results results to the diversity of measures that have been employed to assess PA and neighbourhood attributes (333, 334) and emphasize the need for more (and high quality) research on this topic.

2. Research Gaps

Whilst the focus on individuals is important to isolate the effects of biological and behavioural factors on health outcomes and on the probability to live longer, measuring inequalities between places is perhaps more relevant from a public health point of view. Public health highlights the importance of determining the population causes of health and disease and the importance of conducting population-wide interventions to modify the underlying causes, which are usually social and economic in nature. We do not know yet where in Europe people live longer or lesser, at least taking Europe as a whole and using a fine geographical scale. This lack of knowledge poses a challenge for setting priorities and developing appropriate public health intervention programs and policies.

Spatial inequalities in life expectancy at birth and overall mortality have been acknowledged by (almost exclusively) studies conducted in Anglo-Saxon countries, but very few have looked at the geographical arrangement of old-age survival, which is currently one of the best indicators of mortality dynamics and regional development in low-mortality, high income countries. This probably derived from the belief that inequalities in health manifest earlier in life (observed in premature mortality) and that they tend to decrease as age advances. It lacks a comprehensive view of the spatial inequalities in old-age survival in Europe as a whole (not as fragments).

A line of studies have looked for the presence of geographical niches of extreme survival in defined regions. These investigations were able to identify areas where people live longer than expected but they ignored the areas where older people fall beyond average survival. Furthermore, most of these studies lack robustness in terms of statistical methods. Small area analysis requires robust statistics that allow accounting for random fluctuations and spatial autocorrelation. By using appropriate spatial analysis, we are capable to identify places where population enjoys very high or very low survival, and to estimate the impacts of various socioeconomic and environmental risks. The identification of this areas and underlying factors would allow improving old-age survival, which as diverse studies have shown is highly plastic and vulnerable to societal influences.

There is also insufficient knowledge on the contribution of the physical environment and access to healthcare on the spatial inequalities in health. There is evidence that socioeconomic deprivation is a very influential determinant, but we do not know whether it exerts the same effect in all European countries and regions. We know that physical environment can affect population health too, and, more importantly, it cannot be detached from the socioeconomic environment. Furthermore, good healthcare provision can, for instance, ameliorate the negative impact of poor physical and socioeconomic environment. Evidence-based environmental measures of socioeconomic, physical and healthcare circumstances are currently lacking.

In a time where excess information (not lack of information) is a problem, multivariate indexes are becoming increasingly valorised because they summarize a multitude of factors about the same domain into a single indicator capable to describe the multi-dimensional nature of the concepts they want to measure. Multivariate indexes of socioeconomic deprivation are common in the UK but in the other European countries these indexes just started being developed and applied to public health and local planning. Diverse studies have created their own deprivation indexes but the rational and the methods of each differ considerable which hampers any kind of transnational comparison. The same applies to environmental deprivation. And, as far as we know, no ecological indexes of access to healthcare exist.

Physical activity is a key predictor of old-age survival and it has been increasingly recognized that PA is influenced by contextual determinants of the neighbourhoods where people live. Among the already detected environmental correlates of PA, some still show mixed evidence and no definite answer to the question “how neighbourhood environment affects PA?” exists. Studies focusing on older population are comparably fewer, whilst older adults constitute the population group which more likely suffers the influences of the residential surroundings. More importantly, Southern Europe has been completely disregarded.

In this European region the phenomenon of population ageing is more pronounced and, due to financial constraints, populations would benefit more from population-wide interventions. Although findings from individual level studies are thought to be good enough to be generalized, when it comes to built and social characteristics of the neighbourhoods, the diversity of urban morphologies across the Europe do not allow such extrapolations. Moreover, most studies were undertaken in large metropoles, lacking studies about smaller urban areas.

3. Aims

The main aim of this thesis is to identify and determine the magnitude of the spatial inequalities in the old-age survival in Europe, Portugal and Porto municipality, using the smallest geographical units possible, and to assess the association with socioeconomic, physical and healthcare environment.

Using secondary and primary data sources we address four specific objectives:

1) To develop a measure of old-age survival to be used as alternative of life expectancy in late life and to analyse its spatial distribution in Europe, Portugal and Porto municipality. (papers I,V, VI)

2) To create and validate multivariate ecological indexes of socioeconomic deprivation, physical environmental deprivation, and access to healthcare. (papers II and III)

3) To determine the ecological association between the previously developed indexes and old-age survival in Europe, Portugal and Porto municipality, analysing cross-national differences and possible interactions between the different determinants. (papers IV, V, VI)

4) To test whether PA (one of the most important determinants of old-age survival) among the older adults from Porto is influenced by the physical and socioeconomic characteristics of the neighbourhood. (papers VII, VIII, IX)

In sum, this thesis therefore seeks to contribute to answer a fundamental question, how and to what extent do social and environmental determinants affect the inequalities in old-age survival and active ageing?

4. Methods

4.1. Chapter introduction

This chapter describes the data sources from which we derived the outcomes under analysis, address georeferencing procedures (paper IX), as well as the construction of the multivariate indexes used as covariates (papers II and III). Details on the data processing, variable categorization, and statistical analysis are contained in each scientific article of in this thesis.

4.2. Outcomes

4.2.1. Old-age survival

The life table and derived life expectancy is the most widely used indicator to quantify the probability of survival at birth and at any age. However, information on mortality disaggregated by gender and age group is rarely disclosed for small areas. And even when life tables are available for small areas, resultant life expectancy estimates might be biased. As population size decreases, the standard error increases and it becomes increasingly difficult to show statistically significant differences between areas in term of life expectancy (336). This effect is quite visible for populations smaller than 5000 inhabitants (337), not uncommon when dealing with small areas. Errors can reach two years within populations around 5000 inhabitants and 8 years in the 1000 inhabitants range (336). Moreover, studies have shown that life expectancy after 85 and 95 years of age becomes increasingly overestimated as the population size diminishes due to the presence of zero death counts in these open ended age groups (336).

Due to these constrains, authors have purposed methods of assessing old-age survival that relies on population census, instead of mortality (89, 93, 97). Some of these indicators “track” older population through time and space to estimate how many have survived beyond the average lifespan, resulting in a survival rate at advanced ages. This approach allows minimizing the unknown effect of migration and low birth rates. In areas where migration is high and birth rates are low, the use of total population as denominator is inappropriate, as we would artificially inflate the survival rate. Choosing the population aged 75 years old or more as denominator is more suitable since migration at advanced age tends to be residual.

Because these indicators deal with population that has surpassed the average lifespan (i.e., exceptions to the rule), they might be somehow measuring healthy ageing, assuming this group of exceptionally long-lived people enjoy better health that those that died prematurely or at mean age of death.

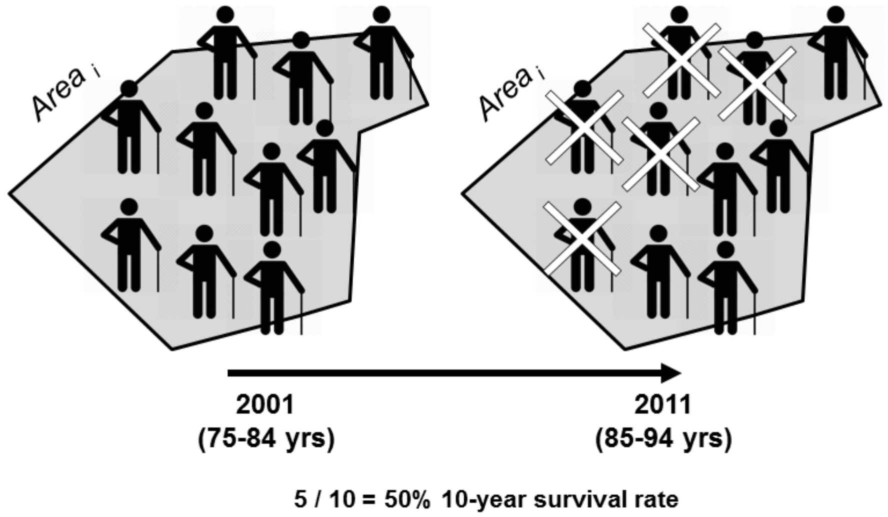

Figure 7. Scheme depicting the method of estimation of old-age survival based on census data.

In this thesis we created a modified version of these indexes by calculating a ten-year survival rate indicating the proportion of the population aged 75-84 years in a census year who survived to 85-94 years old, by gender and area, as schematized in Figure 7. This index was built under the assumption that those aged 75-84 years are the same group of people of those aged 85-94 years old ten years after, i.e., they belong to the same "cohort".

Before applying this indicator we tested whether (as expected) it was correlated with the mortality rates at older ages, say, between 75-84 years of age, available at municipality level in Portugal. We also tested if survival rates calculated after excluding foreign born inhabitants yielded statistically different results than all-residents survival rates. That way we were able to assess whether or not our indicator was affected by senior immigration. Statistically significant Spearman correlation coefficients of 0.999 and -0.507 were obtained for the relation between the 10-year survival rate (2001-2011) and the same rate after excluding foreign residents and the mean mortality rate between 75-84 years of age (2001-2011), respectively. These results suggest it is a valid measure of old-age survival. There is always the possibility that old-age survival measured by these indexes is affected by internal migrations. We could not assess the impact of that phenomena. But evidence suggests that first, migration after 75 years of age is residual (338); second, the distance between the place of birth and place of death tends to be rather small (98); and third, internal migration, at most, hidden spatial and socioeconomic inequalities in health (339).

After data acquisition, similar indicators were created for the small areas of eighteen European countries. Other countries were not included because official publications lack information about the population counts of older age-groups.

This was the key outcome under analysis in this thesis. Naturally, due to problems related to small numbers statistical methods were used to smooth survival rates and to account for the non-independence between observations (spatial autocorrelation). Due to computational advantages and ability to integrate complex hierarchical structures we used Bayesian spatial models.

4.2.2. Physical activity

Data on PA was obtained from the EPIPorto cohort. The cohort was constituted in 1999-2003 comprising a representative sample of 2485 adults (≥18 years of age) residing in Porto municipality. As previously described (340), participants were recruited by random digit dialing using households as the sampling frame. After assessing the number and age of the residents of each household, a simple randomization was applied to select one eligible person among the permanent adult residents. In the case of a refusal, no replacement was permitted. The response rate was 70%, resulting in a total of 2485 participants (341). The local ethics committee (São João Hospital) approved the study protocol. The study was carried out according to the Helsinki Declaration and all participants completed the informed written consent form. Evaluations took place at the Department of Hygiene and Epidemiology of the Faculty of Medicine of University of Porto.

1999-2003 ***Baseline***	**2005-2008** ***1st Follow-up***	**2013-2014** ***2nd Follow-up***
2485 participants (70% response rate) Mean (sd) age 52.9 (15.2) yrs 26.1% aged ≥65 years	1943 participants (78.2% re-evaluated from the initial cohort) Mean (sd) age 57.4 (14.7) yrs 32.7% aged ≥65 years	995 participants (40% re-evaluated) Mean (sd) age 63.1 (12.8) yrs 47.7% aged ≥65 years

Figure 8. Schematic presentation of the EPIPorto study design.

The first follow-up evaluation took place from 2005–2008, when 1943 participants were contacted but 261 participants refused to participate, resulting in a response rate of 86.6%. At this point 78.2% of the initial sample was evaluated. In 2013-2014 the second follow up evaluation occurred. 40% of the initial sample was evaluated (Figure 8).

In papers VII, VIII and IX, cross-sectional in nature, we have used only data from the baseline evaluation (1999-2003) and the first follow-up evaluation (2005-2008).

Evaluations were conducted by trained interviewers using a standard structured questionnaire, comprising information on social, demographic, past personal and family medical conditions, and behavioural characteristics (diet, smoking, alcohol intake, PA). Extensive physical examination was also conducted, which included anthropometrics, blood pressure measurements, echocardiogram and electrocardiogram, blood sample analysis, among others. Physical examination was performed during the morning after a 12-hour over-night fasting by a team composed of nutritionists, biochemists, pharmacists, nurses and physicians.

Physical activity was measured using a questionnaire, EPIPorto Physical Activity Questionnaire, exploring all occupation, household and leisure-time physical activities, detailing the duration (hours per week) and intensity of each activity. For our study we used only time spent in leisure--time PA because it was the only type of PA that could be potentially affected by the characteristics of the neighbourhood of residence. No question on PA for daily transportation was available.

Table 1. Summary of the variables from the EPIPorto Physical Activity Questionnaire used in our study (adapted from (329)).

Variable		Description	Inclusion
Rest Physical Activity (minutes/day)		Time spent in resting activities as sleeping or lying quietly.	No
Occupation Physical Activity (minutes/day)		Time spent at work as sitting or light office working; standing or walking (light effort); standing or walking or walking downstairs, carrying objects; heavy physical work.	No
Household Physical Activity (minutes/day)		Time spent in household tasks such as cooking or washing dishes or ironing; cleaning, food shopping or playing with children; home repairs in gardening.	No
Leisure-time Physical Activity (minutes/day)	Sedentary METs*=1.5	Time spent in sedentary activities (sitting reading, writing, playing cards, etc.)	No
	Light METs=2.5	Time spent in light leisure-time activities (casual walking, golfing, table tennis, billiards, etc.)	**Yes**
	Moderate METs=5.0	Time spent in moderate leisure-time activities (walking at moderate pace, tennis, dancing, swimming, cycling, etc.)	**Yes**
	Vigorous METs=7.0	Time spent in vigorous leisure-time activities (running, basketball, football, athletics, etc.)	**Yes**

*METs – Metabolic Equivalents

To assess the relationship between objectively measured neighbourhood characteristics and health and health behaviours, it was necessary to determine the exact location of the residence of each participant through georeferencing methods, fully discussed in next section (paper IX).

4.2.2.1. Tools for Address Georeferencing – Limitations and Opportunities Every Public Health Professional Should Be Aware Of (paper IX)

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Data Availability: The authors confirm that, for approved reasons, some access restrictions apply to the data underlying the findings. Data used in this study came from the EPIPorto Project. The EPIPorto study protocol was approved by the Hospital São João Ethics Committee, in 1996, and it is under the responsibility of Professor Henrique Barros, director of the Institute of Public Health and of the Department of Epidemiology, University of Porto Medical School. In the present study the authors used individual-level information - exact address location, health-related behaviors and anthropometric measures - which cannot be disseminated due to confidentiality issues. The EPIPorto study protocol is in accordance with the Helsinki Declaration principles, which means 'Every precaution must be taken to protect the privacy of research subjects and the confidentiality of their personal information.' Nevertheless, a formal request to the person responsible for the study (Professor Henrique Barros) can be made by anyone interested in developing scientific research based on data collected within the EPIPorto study. Further information can be found at the Institute of Public Health website: http://www.ispup.up.pt/index.php?cid=Coortes&lang=en.

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RESEARCH ARTICLE

Tools for Address Georeferencing – Limitations and Opportunities Every Public Health Professional Should Be Aware Of

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Abstract

Various address georeferencing (AG) tools are currently available. But little is known about the quality of each tool. Using data from the EPIPorto cohort we compared the most commonly used AG tools in terms of positional error (PE) and subjects' misclassification according to census tract socioeconomic status (SES), a widely used variable in epidemiologic studies. Participants of the EPIPorto cohort ($n=2427$) were georeferenced using Geographical Information Systems (GIS) and Google Earth (GE). One hundred were randomly selected and georeferenced using three additional tools: 1) cadastral maps (gold-standard); 2) Global Positioning Systems (GPS) and 3) Google Earth, single and in a batch. Mean PE and the proportion of misclassified individuals were compared. Google Earth showed lower PE than GIS, but 10% of the addresses were imprecisely positioned. Thirty-eight, 27, 16 and 14% of the participants were located in the wrong census tract by GIS, GPS, GE (batch) and GE (single), respectively ($p<0.001$). Misclassification according to SES was less frequent but still non-negligible −14.4, 8.1, 4.2 and 2% ($p<0.001$). The quality of georeferencing differed substantially between AG tools. GE seems to be the best tool, but only if prudently used. Epidemiologic studies using spatial data should start including information on the quality and accuracy of their georeferencing tools and spatial datasets.

Background

Health-related events, such as births, diseases and deaths, as well as environmental hazards and socially vulnerable areas, can be located on a map using a terrestrial

Competing Interests: The authors have declared that no competing interests exist.

reference, that is, they can be georeferenced. The exact location of such events help health scientists, in particular epidemiologists, to answer questions involving the word "where?": "where are people born and where do they live, get sick and die?", "where are the sources of exposure?", "where can policy makers intervene to reduce risks or improve access to health services?"

The link between health and geography is not recent. Indeed, one of the first known disease maps dates back to 1789 and was made by Seamon and Pascalis, who georeferenced yellow fever cases in New York [1]. In 1854, John Snow's well-known map of cholera deaths in London became a milestone in modern epidemiology [2].

For centuries maps were almost exclusively produced by cartographers and geographers. The increased use of Geographical Information Systems (GIS) since the late 1980s, plus the larger availability of environmental, socioeconomic and health data, now allows any professional to easily access user-friendly tools to georeference, visualize and analyze spatial data. Address georeferencing (AG) tools have also increased – some are expensive, others freely available, some tremendously complicated and others straightforward. Thus, users need to weigh up the pros and cons of each tool and choose the tool that best suits their research goals. But, at present, there is no complete assessment of the quality of the most widely used AG tools.

The risk of biased findings derived from the inappropriate use of cartographic tools increases proportionally, and directly, with the number of GIS users and spatial epidemiological studies [3, 4]. Errors are particularly frequent during the integration of data from diverse sources, e.g., intersecting address locations with ecological variables. Despite the familiarity of epidemiologists and public health practitioners with concepts such as bias, error and confounding, they have frequently lacked knowledge of the basic concepts of cartography, which (depending on how one deals with them) can "make or break" a GIS investigation [5].

In the present study we aim to compare the different address georeferencing (AG) tools that are currently available with a gold-standard. We evaluate their positional accuracy but, particularly, the frequency of individuals' misclassification using a widely used variable in epidemiologic studies – area-level socioeconomic status. These assessments are conducted using data from a population-based cohort of Porto municipality (Northern Portugal).

Some basic concepts of cartography and quality of spatial data

Georeferencing is usually the first stage in the process of spatial data analysis and it consists of converting a description of a location – for instance an address – to a position on the earth's surface. Georeferencing an address can be made by a pair of coordinates obtained from field survey, either using GPS (Global Positioning System) receivers or topographic instruments, which tend to be more accurate but also time-consuming and expensive; or through computerized systems, using street maps (GIS or online mapping tools such as Google Earth, GE).

Spatial datasets, like any type of data, are prone to errors. Thus, three fundamental concepts have to be kept in mind – precision, bias and accuracy. **Precision** refers to the dispersion of positional random errors and it is usually expressed by a standard deviation. **Bias**, on the other hand, is associated with systematic errors and is usually measured by an average error that ideally should equal zero. **Accuracy** depends on both precision and bias and defines how close features on the map are from their true positions on the ground [6]. So, despite being frequently confused concepts, high precision does not necessarily mean high accuracy. But both depend greatly on the map scale.

All maps have inherent positional errors, which depend on the methods used in the construction of the map. The **scale** is the ratio between a distance on the map and the corresponding distance on the ground. The maximum acceptable positional error (established by cartographic standards) is determined by the map scale. Therefore, the choice of map must take into consideration the scale in which it was created in order to guarantee a positional accuracy that meets the objectives of the study. Some less informed users believe that by zooming in a map they are improving its accuracy and precision. That is not true: accuracy and precision are tied to the original map scale and by zooming in a map within a GIS users are increasing its inherent positional errors.

Address georeferencing also has associated bias, precision and accuracy and its quality depends on the combination of two factors: positional accuracy and completeness [7, 8]. Poor **positional accuracy** might perturb cluster detection and affect the magnitude of regression coefficients – random errors will push coefficients towards the null, whereas systematic ones will underestimate/ overestimate associations. **Completeness** is the proportion of records that could be georeferenced and it is evaluated using match rates. Low match rates might reduce statistical power and, eventually, produce biased results due to so-called non-random missingness (match rates differ throughout geographic areas and population strata) [9]. High match rates depend on accurate and detailed address information (known as attribute accuracy and precision) and reference street map.

Some health studies have been conducted using GPS receivers. Be aware, however, that the characteristics of the receivers influence the quality of georeferencing too: the more precise and accurate (positional errors under 1 mm), mostly used in army, engineering and cartography are highly expensive; whereas the most affordable, widely used in epidemiologic studies, have a considerable positional error ranging from 10 to 20 meters.

Knowing the limitations of each spatial dataset is imperative but not enough; usually researchers want to assess the relationships between health data and exposures from the physical and socioeconomic environment, profiting from the potential to combine different spatial data using GIS. GIS inherits the errors from each layer of information. For instance, if the positional accuracy of the AG is 20 meters and we want to overlay a census tract map with a positional accuracy of 5 meters, we could easily fail to pinpoint the participant's address to its actual census tract, as the highest achievable accuracy is that of the least accurate spatial dataset. Eventually, that could lead to so-called **cascading**, as errors propagate from a layer to another, amplifying their effects. Such unpredictable impacts are carefully addressed in the remainder of this article.

Methods

Setting

Located in the northwest of Continental Portugal, Porto municipality has approximately 250,000 inhabitants distributed across 41.7 km^2. It is near the Atlantic coast, along the Douro River estuary (Figure 1). Historically, Porto is an industrial and port city and is the second-largest of Portugal. Porto is a homogeneous city in terms of socioeconomic status (SES) - 50% of the population lives in medium SES areas (Figure 1). The spatial distribution of the areas by SES follows a pattern – areas with similar SES tend to be close to each other. Porto also presents a compact urban design (relatively high residential density with mixed land uses).

Data

We used data from the EPIPorto cohort, which started in 1999 and comprises a random sample of 2485 adults (⩾18 years old) living in Porto [10]. Each participant's address of residence was recorded and used for AG. To improve the original address quality, and subsequent georeferencing match rate, all addresses were screened, standardized and parsed.

All subjects gave written informed consent to participate at the time of enrolment. The EPIPorto study protocol was approved by the Local Ethics Committee (São João Hospital) and is in accordance with the Helsinki Declaration principles.

Porto digital map with street centerlines was used as the street reference map for GIS-based AG. Each street segment comprised the following components: direction ('to' and 'from' node), door number range, name, type (avenue, road, square, etc.) and zip code. Additionally, we acquired a digital map of the census tracts (neighbourhood equivalent) in Porto, then classified according to three discrete classes (from most to least deprived) of socioeconomic status (SES) [11] (Figure 1).

Briefly, that classification was built upon a set of 47 variables available in the 2001 Census at the census tract level. After careful selection (based on statistical criteria and meetings with specialists) the final SES classification included 11 variables relating to the population's age distribution, education level, occupation, and housing conditions (see table below).

To create a summary measure that captured area-level SES, latent class analysis models were run to identify census tracts with similar characteristics. The number of classes was defined according to the Bayesian information criterion, the Akaike information criterion, entropy and interpretability.

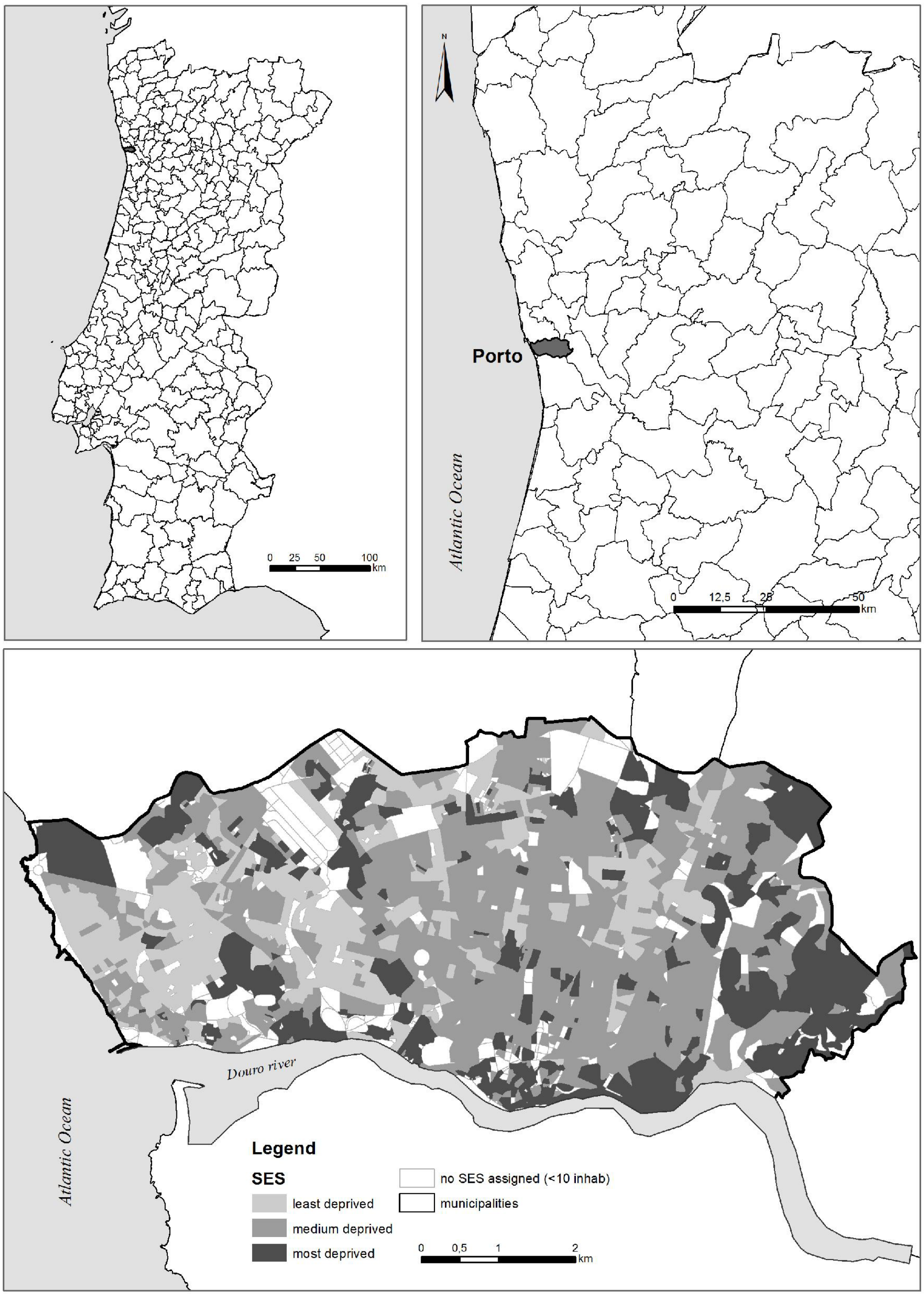

Figure 1. Study Area Location – Porto, Northern Portugal.

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Class 1 (least deprived) accounted for 23% of the total number of census tracts. These areas were composed of younger and highly educated populations. Housing conditions were good and housing expenditure was high, whereas unemployment rate was low. Class 2 (medium deprived) accounted for 47% of the census tracts. These areas were composed by older populations with medium education levels. They were characterized by intermediate proportions of damaged buildings, levels of attractiveness and housing expenditure. Finally, class 3 (most deprived) accounted for 30% of the census tracts. These areas were characterized by a medium ageing index and low values of education attainment, employment, attractiveness and housing expenditure.

Census tract's map was used for point-in-polygon overlay operations, in which we attributed a census tract of residence (and corresponding SES) to each participant according to its point positions determined by the different AG tools used.

Address georeferencing using GIS

All participants, for which addresses were available, were georeferenced using GIS ArcView 9.0 [12] which, by interpolation, places the address in the corresponding street segment and assigns a pair of coordinates.

Addresses were georeferenced in three phases: 1) automatic, when street map names and the address table names fully matched (spelling score >80%); 2) semi-automatic when the spelling score was <80% and georeferencing was done by interactively selecting from a list of possible locations; 3) manual, when the remaining addresses were georeferenced by searching them in analog maps, placing them in the digital map and retrieving their coordinates. If these approaches failed, participants were contacted to provide correct address information or spatial reference points.

Google Earth

Addresses were also georeferenced using GE. Three approaches were followed: 1) one address at each time (single GE) in which the user can intervene and pinpoint the address; 2) in a batch (batch GE) using an application which assigns a code to each georeferenced address according to the AG accuracy (exact address, street centroid, building or residential complex centroid or municipality centroid); and 3) in a batch GE without the previous application.

We chose to utilize multiple approaches to consider an important limitation of GE georeferencing: when this tool cannot locate a certain address, it automatically (without alerting the user) searches through other geographical levels (street, municipality, country), until it finds a match, and assigns a pair of coordinates from the centroid of such area. Contrary to what was done for GIS-based AG, addresses that GE could not find and/or precisely georeference were not georeferenced again using manual techniques.

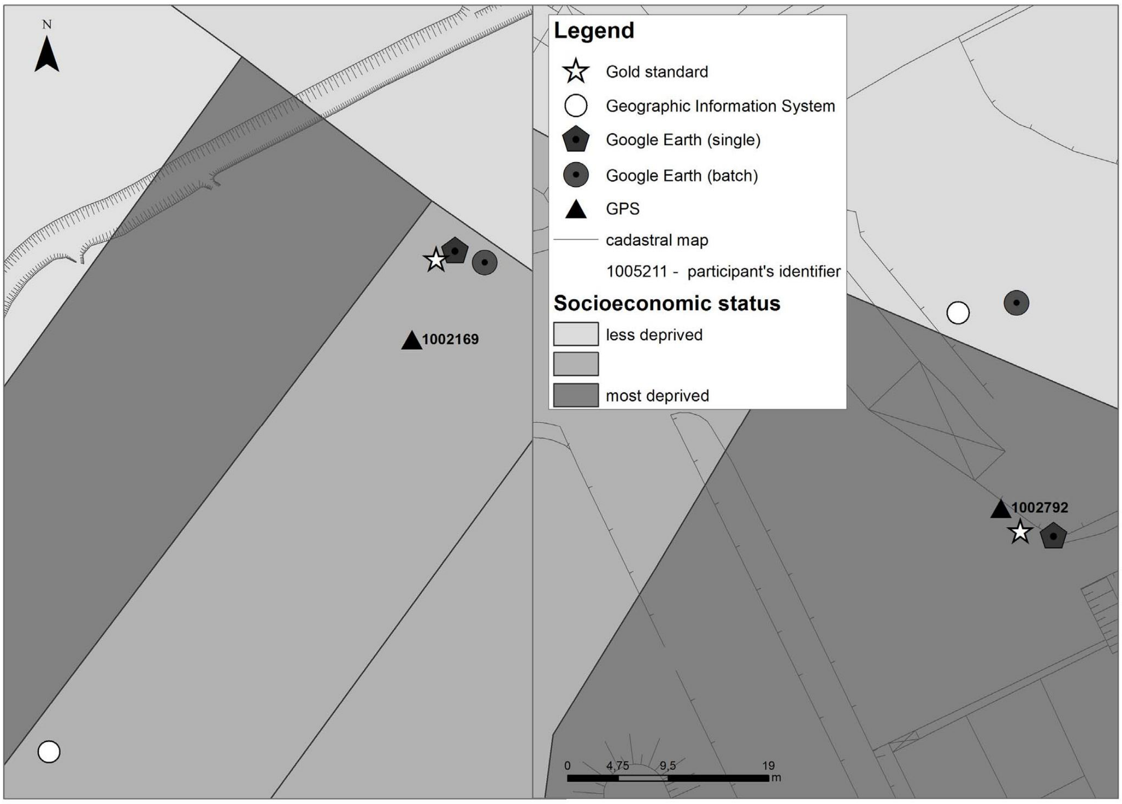

Figure 2. Point position of two participants according to address georeferencing method.

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GPS measurements and field survey

To compare different AG tools in terms of positional error (PE) and misclassification frequency, we selected a random sample of 100 participants from the EpiPorto cohort. Beyond GIS and GE (single and batch), two alternative AG tools were chosen: using GPS receivers and using cadastral maps (ground truth) during field survey. Addresses were distributed evenly by the team and georeferenced using hand-held GPS receivers.

The ground truth location of each address (called here, gold-standard) was assessed by identifying the location on a cadastral map of the city (scale 1/2000). Cadastral maps are detailed maps, which show both natural and built features and are produced with high accuracy standards compatible with large scales (usually between 1/1000 and 1/5000).

Regarding the 100 addresses that were georeferenced by the four AG tools, estimates of the time spent using each tool were quite varied. The assessment of ground-truth and GPS location took 7 days (8 hours each), totaling about

Table 1. Results from Google Earth address georeferencing.

Georeferenced	No. (%)
Exact address	2050 (84.6)
Street centroid	209 (8.6)
Building or residential complex centroid	51 (2.1)
Municipality centroid	66 (2.7)
Not georeferenced	**47 (1.9)**
Total	2423 (100.0)

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56 hours. Address georeferencing using Google Earth batch tool and Geographic Information Systems took a few minutes, since these are completely automatic tools. Finally, to georeference addresses using Google Earth manual tool, investigators needed about 15 hours.

By way of example, Figure 2 depicts the location of two participants according to the AG method.

Statistical analysis

PE was defined as the Euclidian distance (d), in meters, between the gold standard (x_1, y_1) and the locations obtained using the i^{th} other georeferencing tools standard (x_i, y_i) (expression 1).

$$d = \left[(x_1 - x_i)^2 + (y_1 - y_i)^2\right]^{1/2} \qquad \text{(expression 1)}$$

To characterize PE distributions, descriptive statistics (mean, median, and standard deviation) and boxplots were used. The Friedman test for repeated measures was used to compare median positional error between the different AG tools. Post-hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied. Cochran's Q test was employed to compare the proportion of misplaced (census tracts) and misclassified (census tract socio-economic status) individuals between AG tools.

Results

Completeness

The EpiPorto baseline database had a total of 2423 addresses, 5 of which were not georeferenced due to incomplete/incorrect addresses, resulting in a match rate of 99.8%. Using GIS, the majority of the records were automatically georeferenced (71.0%) with a smaller proportion by the semi-automatic (13.1%) or manual methods (15.9%).

Using batch GE AG, 84.6% of the addresses were automatically pinpointed in the exact position and 1.9% could not be georeferenced. The remaining addresses

Table 2. Summary statistics of positional errors (in meters) according to address georeferencing method.

	Median	Mean (SD)	Minimum	Maximum
GIS[a]	16.1	52.0 (100.7)	0.70	704.0
GPS[b]	7.2	7.4 (3.9)	0.34	20.5
Google Earth batch[c]	5.3	30.4 (133.2)	0.1	1240.3
Google Earth single[d]	4.0	5.4 (4.7)	0.0	33.1

[a]Geographic Information System address georeferencing tool.
[b]Global Positioning System.
[c]In a batch using Google Earth address georeferencing tool.
[d]Address by address using Google Earth address georeferencing tool.

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were georeferenced at different precision levels (Table 1). Notice that nearly 10% of them were approximately placed (street and municipality centroids).

Positional Error

We detected statistically significant differences in PE between AG tools ($p<0.001$) (Table 2 and Figure 3). Compared with all alternative AG tools, median PE using GIS was significantly larger, 16 meters ($p<0.001$). On the contrary, GE (single) exhibited the best performance, significantly better than GPS ($p<0.001$). Positional error of methods using a batch of addresses showed highly skewed distributions with maximum positional errors reaching 704 m and 1240 m using GIS and automatic GE, respectively.

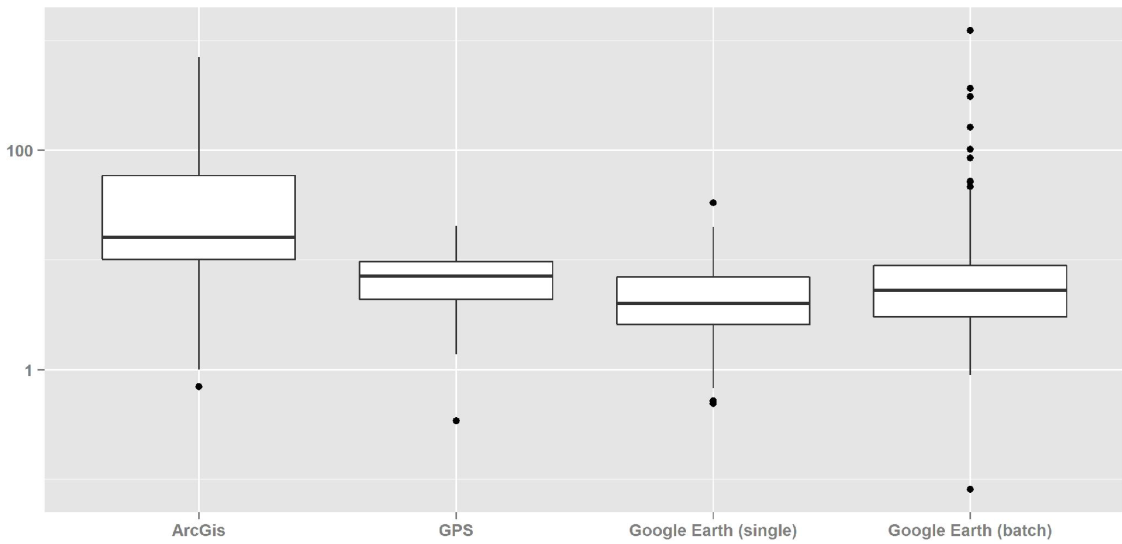

Figure 3. Distribution of positional errors (log-scale) according to address georeferencing method.

doi:10.1371/journal.pone.0114130.g003

Misclassification

Thirty-eight, 27, 16 and 14% of the participants were located in the wrong census tract using GIS, GPS, GE (batch) and GE (single) respectively ($p<0.001$). However, misplaced participants were almost always (more than 96%, regardless the method) positioned in a census tract in the first-order neighborhood, i.e., in a contiguous census tract.

Consequently, because Porto is a homogeneous city, misclassification in census tract SES was less frequent: 14.4, 8.1, 4.2 and 2% using GIS, GPS, GE (batch) and GE (single), respectively ($p<0.001$). Again, GIS georeferencing showed the worst performance, whereas AG using GE (single) stood out as the best method.

The spatial distribution of misclassified individuals (results not shown) showed no spatial pattern. Misclassification in census tract SES also did not appear differential: the proportion of individuals that were wrongly georeferenced in a less deprived census tract was comparable to the proportion of those that were georeferenced in a more deprived census tract.

Discussion

In the present study we compared a number of different address georeferencing tools and characterized them according to the following quality criteria: completeness (match rates) and accuracy (positional error and misclassification). Results showed that GE (single) had the highest match rates and the highest accuracy – lower positional error and misclassification – followed by its automatic version (GE batch), GPS and GIS (ArcGis).

Comparing our findings with the literature on this topic was an arduous task: one single European study was found and the remaining were from the USA; they were from large and heterogeneous urban settings; and different AG tools and datasets types were under comparison. Despite such limitations, the positional error we found for GIS AG fell within the previously reported ranges: estimates varied between 200 meters to 10 meters based on mean and median values, always with some extreme outliers [7, 13–16]. Notice, however, that most previous studies have used the coordinates obtained using hand-held GPS receivers as the gold-standard – accuracy around 10–20 meters – rather than cadastral maps, which are much more accurate – accuracy of 1 meter for a 1/2000 scale map. Regarding the recently available GE batch AG tool, to our knowledge, only one study addressed its positional error (still relative to GPS measurements) [17]. Authors reported a median error of 22 meters, slightly higher than our estimate. No investigation was undertaken to explore the positional accuracy of single GE (that is, searching addresses one at a time with intervention of the operator) or GPS georeferencing.

Statistics on match rates are much more frequent. Most of the studies reported values around the recommended threshold of 80%; lower match rates are considered unacceptable for epidemiological analysis. However, diverse match rates have been described – from 40 to 99% depending on the type of AG

[3, 4, 8, 18–23]. AG processes running exclusively in a batch usually lead to low match rates, unless lenient matching options were defined, which would inevitably compromise positional accuracy. In our study, we achieved a match rate (in a batch) of 71% and 85%, respectively for GIS and GE. When GIS AG was used, the 80% requirement was achieved only after semiautomatic and manual approaches. GE match rates, albeit higher, masked important inaccuracies. When we examined the results from the batch GE AG tool, which assigns a code to each address according to the georeferencing accuracy, a reasonable proportion (10%) of the addresses were only approximately placed (street and municipality centroids), leading to extreme outliers of positional error.

Very few studies reported the percentage of misclassified or misplaced addresses. In our analysis we found that a large number of addresses were placed in the wrong census tract, reaching 38% using GIS, which is in accordance with similar studies [4, 24]. Obviously, area misplacements depend on how coarse or fine our territorial units are. Misclassification can be extremely important when using micro-areas, like ours, but inconsequential when using large administrative divisions. Moreover, even when using micro-areas, a non-differential misclassification might not compromise the study findings (although might lead to underestimation of associations), but differential misclassification might lead to biased findings. For instance, in our study, we found no spatial pattern in the position of misclassified individuals and, comparing the SES of the participants' census tracts attributed using GIS and GE (batch) AG, the SES changes were quite random.

Misclassification in census tract (neighborhood) SES was lower, but still non-negligible (14% using the GIS). We found no similar study assessing the misclassification of exposures based on point-in-polygon processes. In our study we observed no differential misclassification, that is, the proportion of individuals that were wrongly georeferenced in a less deprived census tract was comparable to the proportion of those that were georeferenced in a more deprived census tract. However, investigations attempting to determine to what extent misclassification of contaminant exposure affects epidemiological analysis found that the misclassification is extremely high for this kind of small area analysis [7, 13].

Some limitations of our study must be highlighted. Firstly, our findings are based on a single urban setting. Porto is a relatively homogeneous city in terms of the physical and socioeconomic environment. This means that results could be generalizable to other medium-sized urban settings, but not to larger cities or rural areas. However, our study fills a gap in the scientific literature of studies undertaken in medium sized urban settings, especially in Europe, where space is more fragmented and geographical units are, consequently, much smaller. Also hampering generalization, our reference data (street centerlines and census tracts) have their own positional accuracy, which will undoubtedly differ from the ones employed in other contexts. The same extends to the georeferencing tools we used. Secondly, we only examined the misclassification for a single environmental determinant – neighbourhood SES, composed of three levels with a patterned spatial distribution across the municipality. Nevertheless, neighborhood SES is considered in almost every multilevel epidemiological study and the distribution of neighborhood SES tends to be spatially patterned in most urban settings (deprived areas stand near each other like the affluent areas). Our findings are therefore useful for the critical evaluation of results from these studies.

Conclusions

In the present study we aimed to inform epidemiologists and public health practitioners about the fundamental concepts of cartography and demonstrate the advantages and drawbacks of some currently available address georeferencing techniques. Address georeferencing tools differed significantly and the recently available Google Earth batch tool was revealed to be a valuable alternative method relative to GIS, but only if prudently used. There were a considerable amount of misclassified and misplaced addresses, which were universal to all address georeferencing tools. Our results also suggest misclassification errors were random, i.e., non-differential. However, future studies should assess the effect of AG inaccuracies in determining exposures to other area-level determinants (e.g. air pollution, noise, ambient temperature), especially in Europe where spatial analysis has become frequent, but has not been accompanied by methodological assessments on spatial data quality. Further studies are also needed to evaluate the impact of participant's misclassification (regarding a wide range of variables from the physical and socioeconomic environment) on subsequent statistical analysis and conclusions.

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Author Contributions

Conceived and designed the experiments: AIR MFP. Performed the experiments: AIR AO HT AM MFP. Analyzed the data: AIR. Contributed reagents/materials/ analysis tools: AIR AO HT AM MFP. Wrote the paper: AIR.

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4.3. Contextual determinants

4.3.1. Multivariate indexes

An index is a rating scale, a set of values derived from a series of observations of specific variables (5). Indexes give data added value. Multivariate indexes are usually required to grasp complex phenomena such as most environments to which population is exposed, being them social, economic, biogeophysical, among others. Ecological indexes allow us to reduce the number of variables that are necessary to characterize precisely these environments. The use of a large number of variables usually clutter the picture we want to disclose, whereas using too few is usually insufficient to provide a representative picture of the environmental conditions. Indexes solve this problem, simplify the communication and analytical process, being essential to faster decision-making process (343).

A good index must be scientifically valid, that is, be theoretically well-grounded, sensitive to changes; consistent and comparable over time and space; robust and unbiased and based on data of a known and acceptable quality (343, 344). Moreover, an index must be politically relevant, which implies it has to deal with priority areas, be related with amenable conditions, freely available, and at most easy to understand and apply by potential users (344). To be understandable all steps and decisions leading to the final index have to be openly described. There is currently a growing need for ecological indexes both at broader scales, to permit national and international comparisons, and at sub-national, community and city-level to support local interventions (344).

The next sections describe in detail the conceptual framework and construction of three indexes: a socioeconomic deprivation index, a multiple physical environmental deprivation index and an access to healthcare index. The development of the walkability index for Porto neighbourhoods is fully described in paper VI, inserted in the Results chapter, as its construction followed a well-established methodology. The same applies to the creation of the multiple physical environmental deprivation index for Porto, which is simply an adaptation of the national version (fully described in paper III) using higher spatial resolution datasets. We intended to develop them for research purposes, but hopefully they will be directly used in the decision-making process.

4.3.1.1. The Portuguese version of the European Deprivation Index. An instrument to study health inequalities (paper II)

The Portuguese version of the European Deprivation Index. An instrument to study health inequalities

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ABSTRACT
Introduction: Tackling socioeconomic health inequalities is a big public health challenge and ecological deprivation indexes are essential instruments to monitor and understand them. In Portugal, no standard ecological deprivation index exists, contrasting with other countries. We aimed to describe the construction of the Portuguese version of a transnational deprivation index, European Deprivation Index (EDI).
Methods and Materials: EDI was developed under the Townsend theorization of deprivation. Using data from the European Union--Statistics on Income and Living Conditions survey, we obtained an indicator of individual deprivation. This indicator became the gold-standard variable, based on what we selected the variables at aggregate level (census) to be included in EDI, a total of eight. EDI was produced for the smallest areal unit possible (n=16,094, mean/area=643 inhabitants) and resulted from the weighted sum of the previous variables. It was then classified into quintiles.
Results: The first quintile (least deprived) comprised 20.9% national population and the fifth quintile (most deprived) 18.0%. EDI showed a clear geographic pattern – most deprived areas concentrated in the South and in the Inner North and Centre of the country, and the least deprived areas in the coastal areas of North, Centre and Algarve.
Discussion: The development of EDI was grounded on a solid theoretical framework, individual and aggregate variables, and on a longitudinal Europe-wide survey allowing its replication over the time and in any European country.
Conclusion: Hopefully, EDI will start being employed by those interested in better understand health inequalities not only in Portugal but across Europe.
Key-words: deprivation index; poverty; census data; EU-SILC; Europe.

Introduction

Socioeconomic deprivation

Health inequalities have been observed all over the world and tackling them has become one of the top priorities for national and international public health authorities[1]. Health inequalities can be defined as differences in health status or in the distribution of health determinants between different population groups[2]. And this unequal distribution of health is closely linked to socioeconomic deprivation.

Socioeconomic deprivation is far from being a consensual concept. But, to date, the most assenting conceptualization seems to be the one proffered by Townsend in 1970s who argued that deprivation is: 1) a relative ("…state of observable and demonstrable disadvantage relative to the local community or the wider society or nation to which an individual, family or group belongs") and 2) a multidimensional concept ("…the concept of deprivation covers the various conditions, independent of income, experienced by people who are poor")[3,4]. Summing up, deprivation is a wider concept than poverty since it covers more than disposable income; deprivation refers to the lack of fundamental needs, which are context- and time-specific.

Diverse ecological deprivation indexes, also known as area deprivation indexes, have been created to better understand health inequalities. Because they include a wide range of variables, are considered to better reflect the multi-dimensional nature of deprivation. They started being developed in 1970s in the United Kingdom (UK)[5], but currently almost every European country has its own deprivation index, or uses a well-established measure such as Carstairs & Morris[6] or Townsend index[7]. With these measures researchers have been able to demonstrate that living in deprived areas is associated with worst health outcomes[8-10]. And, as the statistical arsenal became more sophisticated, studies have even showed that this relationship occurs independently of the individual level deprivation[10,11].

Portuguese studies using ecological deprivation indexes

In Portugal studies addressing socioeconomic inequalities in health are few, but they have been growing in number since the 2000s. Ecological deprivation has been used as a determinant for a wide variety of outcomes – suicide and injuries[12,13], all-cause[14-16], cause-specific[15-17] and avoidable mortality[18], body mass index[19,20], hip fractures[21], infections[22], tobacco related-diseases[23], and health-related behaviors such as physical activity[24-26] or fruit and vegetable consumption[26,27]. For such small number of studies (17 studies) the amount of deprivation indexes that is being used is rather large (8 different indexes).

Table 1. Characteristics of the ecological deprivation indexes used in Portugal (2009-2015).

Name of the index	Year	Geographical extent	Unit	No. variables	Variables	Choice of the variables	Studies
Deprivation score[20]	2009	Lisbon Metropolitan Area	Parish	3	- male unemployment - unskilled worker employment - individuals living in shanty household	Based on Carstairs & Morris[6]	20,27
Multiple Deprivation Index (MDI)[44]	2010	Lisbon Metropolitan Area	Parish	3	- unemployed people - unskilled employed workers - persons living in slum conditions	Based on Carstairs & Morris[6]	44
Neighborhood socioeconomic latent classes[26]	2013	Porto municipality	Census blocks	11	- retired individuals - families with an individual aged ≤15 years - aging index - illiterate subjects - subjects with higher education - subjects with lower occupation - unemployment rate - mean expenditure on owned housing - mean expenditure on rented housing - attractiveness - buildings with reparation needs	Variables chosen based on expertise and statistical criteria	19,22,24-26
Index of socioeconomic deprivation[13]	2013	Lisbon Metropolitan Area together with other European urban areas	Parish	5	- unemployment rate - manual workers - young people with primary or lower level of education - young people with university education - foreigners from low-income countries	Conceptual statistical choice. Comparable between areas. P_2-distance method (similar to PCA*)	13-15,18
Socio-material deprivation index (Índice de Privação Sociomaterial)[17]	2014	Nationwide	Municipality	3	- illiteracy - unemployment - households without a toilet	Based on Carstairs & Morris[6]	17
Area-based socioeconomic (SE) indicator[23]	2015	Nationwide	Parish	6	- people without schooling - people with secondary education - residents employed in industry, trade and service occupations - residents employed in industrial and manual occupations - dwellings overcrowded - owner occupied houses	Variables chosen based on expertise and statistical criteria	23
Municipality socioeconomic status (SES)[21]	2015	Nationwide	Municipality	17	- population by age groups and sex - retired individuals (by sex) - widows - individuals receiving social support - illiteracy - aging and youth dependency indexes - individuals living alone - mean number of rooms per household - mean number of individuals per household - unemployment rate - subjects with higher and basic education - subjects by category of occupation - income - residences and buildings with/without public water supply, mains, or otherwise - households with heating and by type of heating	Variables chosen based on expertise and statistical criteria (PCA)	21
Material deprivation index[16]	2015	Nationwide	Municipality	3	- illiteracy rate - unemployment rate - houses without a toilet	Based on Carstairs & Morris[6]	12,16

** PCA=Principal Component Analysis*

Their characteristics are summarized in Table 1.
This diversity of ecological deprivation indexes reveals growing interest in the topic, but hinders study comparability, because the variables and the theoretical conceptualization beyond each of those indexes differ substantially. Also, a shortcoming of those measures has to do with the fact they were often produced for large and heterogeneous areas, such as parishes and municipalities, limiting its utility in regional and local planning. In Portugal no standard deprivation measure covering the entire country exists, contrasting with other countries[28-33], where statistical offices and public health institutions have been making an effort in this direction.

Recently, a multinational and multidisciplinary team joined efforts to create a cross-national ecological deprivation index for the small areas of England, France, Italy, Portugal, and Spain[34,35]. This index was developed using as bedrock the Townsend theorization of deprivation. With data from a European-wide survey, which provided information on the perceived and objective poverty, a measure of individual deprivation was obtained. This measure became the gold-standard variable, based on what the variables at aggregate level were selected to the ecological deprivation index, called European Deprivation Index (EDI). The variables that compose the individual and ecological deprivation indicators vary by country, as expected, but the fact that they were chosen under the same methodological and theoretical framework makes EDI comparable between countries.

Although a previous paper from the team has described the development of EDI[34], the aim of this paper is to describe in more detail the construction of the Portuguese version of the European Deprivation Index, as well as its statistical and spatial distribution.

Methods

The construction of the EDI involved three key methodological steps, which will be fully described: (1) constructing an individual deprivation indicator; (2) identifying the variables that were available at individual level (survey) and at aggregate level (census) and (3) constructing an ecological deprivation index, the EDI.

1) Constructing an individual deprivation indicator

This first step of the construction of EDI relied exclusively on the European Union-Statistics on Income and Living Conditions, EU-SILC[36]. This survey is organized by the European Union (EU), and it is specifically designed to measure deprivation and its domains (income, social exclusion, housing conditions, labour, education and health). In Portugal, EU-SILC is being implemented annually by Statistics Portugal (INE, Instituto Nacional de Estatística) since its first wave in 2004. We used EU-SILC 2006 cross-sectional survey which covered all 26 EU countries.

In Portugal this survey took place between May and July 2006 and included 5416 households, 12,071 individuals, 10,148 of them aged 16 years old. The households were chosen by stratified two-stage sampling, based on the original 2004 sample to guarantee that individuals can be followed longitudinally. All analysis were weighted for non-response and adjusted for sample design to ensure the representativeness of the results.

1.1) Identification of fundamental needs

As referred in the introduction, there is no clear-cut definition of individual deprivation. We based our measure of individual deprivation on the concept of fundamental needs purposed by Townsend, which have been the basis of the UK multivariate indexes of deprivation[28-31].

Fundamental needs are items which are considered necessary in a specific sociocultural context. If the majority of the population possesses these items, it means that those that cannot afford it are in disadvantage. In the Portuguese EU-SILC survey, several items were not possessed by the majority of households, and so were discharged. Only items possessed by more than 50% of the households were considered fundamental needs. For instance less than 50% of the Portuguese households had a computer, leading to discharge this variable. Items that most individuals could not afford (>50%) were also disregarded. For example, over 60% of the Portuguese households could not afford taking a week's annual holiday away from home; this variable was consequently excluded. Table 2 lists the items considered fundamental needs in Portugal.

Table 2. Identification of fundamental needs: proportion of Portuguese households that indicated that specific goods and services were not within their means (EU-SILC survey 2006, n=5416 households).

Type of needs	% of households that cannot afford
Keeping your house adequately warm	41.6%
Using your own means to cover a necessary yet unplanned expense	18.2%
Having a personal car	11.6%
Having a phone (including mobile phone)	5.4%
Having a washing machine	4.8%
Eating a meal containing meat, fish, or the vegetarian equivalent once every two days	4.4%
Having a colour TV	1.1%

1.2) Identification of fundamental needs associated with objective and subjective poverty

Poverty and deprivation are closely related. Poverty has an objective (income) and a subjective dimension (perceived poverty). Thus, to identify the fundamental needs that were associated with poverty, we opted to include only those that were associated with both objective and subjective poverty. These two dimensions of poverty were ascertained in EU-SILC survey.

Objective poverty was determined by income. An individual is considered at-risk-of-poverty whenever his/her household income is below 60% of the national median equivalised disposable income. The equivalised disposable income is equal to the net income of the household after social transfers divided by the number of household members[37]. In Portugal, the at-risk-of-poverty threshold, in 2006, was 341 euros per month[38]. Based on that value, 20.7% of the households were considered poor.

Subjective poverty was determined by the EU-SILC Likert-scale question 'ability to make ends meet' (1-with great difficulty, 2-with difficulty, 3-with some difficulty, 4-fairy easily, 5-easily and 6-very easily). To determine the threshold at which a person felt poor we conducted univariable logistic regressions between dependent variable objective poverty ('poor'/'not poor' based on the at–risk-of-poverty threshold), and the independent variable subjective poverty, dichotomized so that it covered all combinations of the answers to the question 'ability to make ends meet'. The Wald chi-square statistic ($\chi 2$) of the different logistic regression models was used to determine the dichotomization with the best fit; the higher the $\chi 2$ the better the fit. In Portugal the answer 1 ('with great difficulty') versus the others (2-6) showed the best fit. Based on that threshold, 15.7% of the Portuguese households were subjectively poor.

From the previously identified fundamental needs (1.1.) only those significantly associated with both subjective and objective poverty were included to create the individual deprivation index. Univariable and multivariable logistic regression models were run to identify them with a significance level set up at of 5%. As a result, five of the seven items of Table 2 were considered fundamental needs: 'Eating a meal containing meat, fish, or the vegetarian equivalent once every two days'; 'Using your own means to cover a necessary yet unplanned expense'; 'Keeping your house adequately warm'; 'Having a phone (including mobile phone)'; and 'Having a personal car'.

1.3) Creation of an individual deprivation indicator

Previously selected five fundamental needs (1.2) were used to create a binary indicator of individual deprivation. Multivariable logistic regression was run to determine the threshold number of fundamental needs that better explained objective and subjective poverty. Wald $\chi 2$ was used for that assessment. The better fit threshold stayed on two fundamental needs, meaning that an individual that could not afford two or more (of the five) fundamental needs was defined as deprived.

2) Identifying and arranging the variables that were available at individual level (EU-SILC survey) and at ecological level (census)

The second step of the construction of EDI involved the use of ecological data from the Portuguese census. We have used data from 2001 Population and Housing Census made available by Statistics Portugal[39]. Portuguese censuses are universal and exhaustive, covering the entire national population. Data was available at census tract level but EDI was built at upper aggregation level, census tract block groups, because a considerable amount of the census tracts had zero counts, not allowing to derivate a deprivation index. In 2001 there were 16,094 census tract block groups, comprising each one an average of 222 households and 643 inhabitants.

Firstly, we assessed which variables from EU-SILC survey were also present in 2001 Census data. A total of eight matching variables were found.

Secondly, we had to recode variables in both datasets (EU-SILC and Census) so that they become comparable (supplementary material 1)

Because we wanted to calculate proportions at ecological level for each of the eight matching variables, we had to find the best way to dichotomize the variables. Some variables could only assume two possible values (such as being unemployed looking for a job; rooms in the household; household with bath/shower and household with indoor flushing), but others could assume more than two (education, occupation, age/sex and household tenure status).

To dichotomize those variables, we conducted logistic regression models to find the best fit (based on Wald $\chi 2$) between the individual deprivation indicator and the multiple category variables (dichotomized in all possible ways). For instance, three models were run to assess the best dichotomization of the variable occupation sector: 'primary versus secondary+terciary'; 'secondary versus primary+terciary' and 'terciary versus primary+secondary'; the last dichotomizaton showed the best fit.

Proportions of those variables, for each census tract block group, were calculated based on the previously chosen dichotomizations: percentage of non-owned households; percentage of households without indoor flushing; percentage of individuals with low education level (≤6th grade); percentage of households with 5 rooms or less (pantries, kitchens, corridors, bathrooms and balconies excluded); percentage of unemployed looking for a job; proportion of female residents aged 65 years or more; percentage of households without bath or shower; and percentage of individuals employed in the primary/secondary sectors (i.e., manual occupations).

3) Constructing an ecological deprivation index, EDI

To determine which variables were to include in the EDI, a multivariable logistic regression was run and only variables significantly associated with the individual deprivation indicator were kept. We kept all the eight variables. Then, the regression coefficients of that model (Table 3) became the weights that were assigned to each of those variables at ecological level.

Next, each ecological variable was normalized to the Portuguese national mean. The score of the Portuguese EDI for each census tract block group resulted from the following equation:

Score = % non-owned households (z-score) × 1.193
+ % households without indoor flushing (z-score) × 1.456
+ % residents with low education level (≤6th grade) (z-score) × 1.292
+ % household with 5 rooms or less (z-score) × 0.404
+ % unemployed looking for a job (z-score) × 0.376
+ % female residents aged 65 years or more (z-score) × 0.255
+ % households without bath/shower (z-score) × 0.060
+ % residents employed in manual occupations (z-score) × 0.013

Table 3. Final model of multivariable logistic regression selecting components of EDI, which were associated with the final individual deprivation indicator, Portuguese EU-SILC (n=10,148).

Variable	β	Odds ratio (95% CI)	p-value
No indoor flushing	1.456	4.287 (4.178-4.400)	<0.001
Low education level (≤6 years)	1.292	3.640 (3.599-3.681)	<0.001
Non-owner	1.193	3.298 (3.273-3.323)	<0.001
Household with less than 6 rooms	0.404	1.497 (1.477-1.518)	<0.001
Unemployed looking for a job	0.376	1.456 (1.443-1.471)	<0.001
Women aged 65 years or more	0.255	1.291 (1.278-1.304)	<0.001
No bath or shower	0.060	1.061 (1.035-1.088)	<0.001
Manual occupation	0.013	1.014 (1.006-1.021)	<0.001

Results

The Portuguese EDI had the following distribution: minimum = -8.155; maximum = 17.249; mean = 0.000 and standard deviation = 2.283. Then, each census block group was classified according to its level of deprivation using the quintiles of the EDI score as cut-offs: 1 (-8.155 to -1.774); 2 (-1.773 to -0.605); 3 (-0.605 to 0.338); 4 (0.338 to 1.581) and 5 (1.582 to 17.249).

The first quintile (least deprived) comprised 2,161,387 inhabitants (20.9% of the national population), the second 2,192,718 inhabitants (21.2%), the third 2,125,503 inhabitants, 20.5%), the fourth 2,014,442 inhabitants (19.5%), and the fifth quintile (most deprived) 1,862,045 inhabitants (18.0%). Due to scarcity of households/population, a residual number of 18 census block groups (22 inhabitants) ended up with no EDI score assigned.

The EDI was also computed at higher aggregation level – parish level (n=4241) and municipality level (n=308).

Fig. 1 and 2 show the geographical distribution of EDI in Continental Portugal and archipelagos. Portuguese EDI shows a clear geographic pattern, being the most deprived areas generally located in the South and in the Inner North and Centre of the country, whereas the least deprived areas are predominantly located in the coastal areas of North, Centre and Algarve.

Maps depicting the spatial distribution of EDI were produced using ArcMap 10.2.1., and statistical analysis was performed using SAS 9.1, SPSS 21 and R 3.1.1.

Discussion

This article describes the methods of construction of an ecological deprivation index, the EDI, which classifies small areas of the entire country, Continental and archipelagos, according to their level of socioeconomic deprivation. To date, no other Portuguese index has covered the entire territory. The development of the EDI was grounded on a solid theoretical framework, used both individual and aggregate variables, and relied on a longitudinal Europe-wide survey that guarantee EDI can be replicated over the time and in any of the 28 EU member states.

Evidence-based, ready-to-use and understandable multivariate measures are highly required by public and political leaders[40]. These measures should be developed with involvement of relevant stakeholders and should use scientifically sound data and appropriate analytical methods[40]. The EDI is a multivariate indicator that included not only material deprivation but other conditions. EDI was grounded on the framework defined by Townsend who defended deprivation is highly dependent on the context and time and, consequently, cannot be measured based solely on material conditions[3,4]. In the development of EDI, we selected fundamental needs associated with both objective (income based) and subjective (perceived) poverty and we have followed the theoretical concept of relative deprivation.

Portuguese EDI was developed based on a European-wide survey (EU-SILC), specifically designed to measure and monitor poverty and deprivation across the EU territory, which legitimize our indicator. The variables were chosen based on an individual index of deprivation, meaning we only

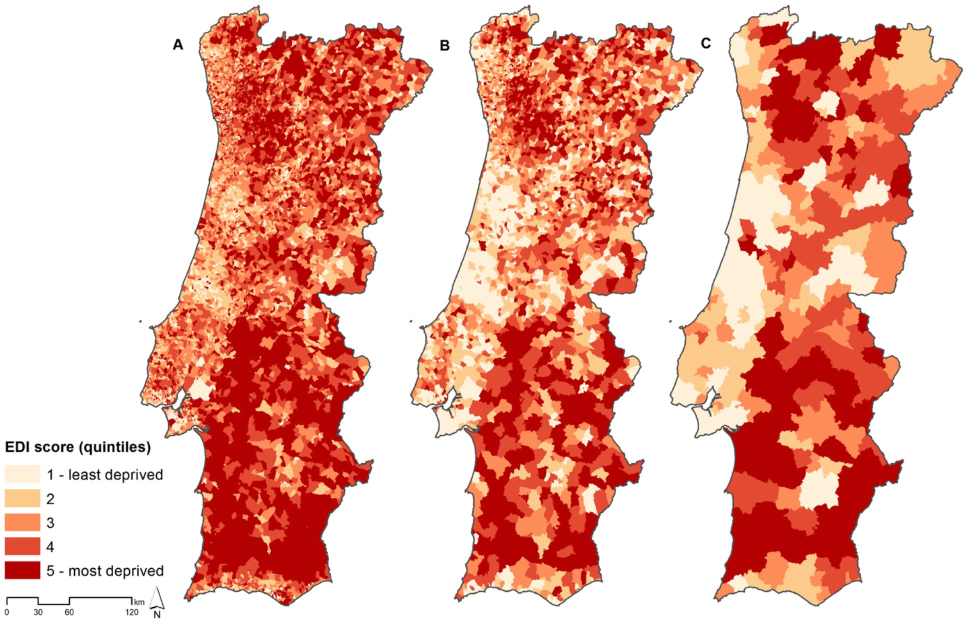

Figure 1. Spatial distribution of the European Deprivation Index in Continental Portugal. (A-census block groups; B-parishes; C-municipalities)

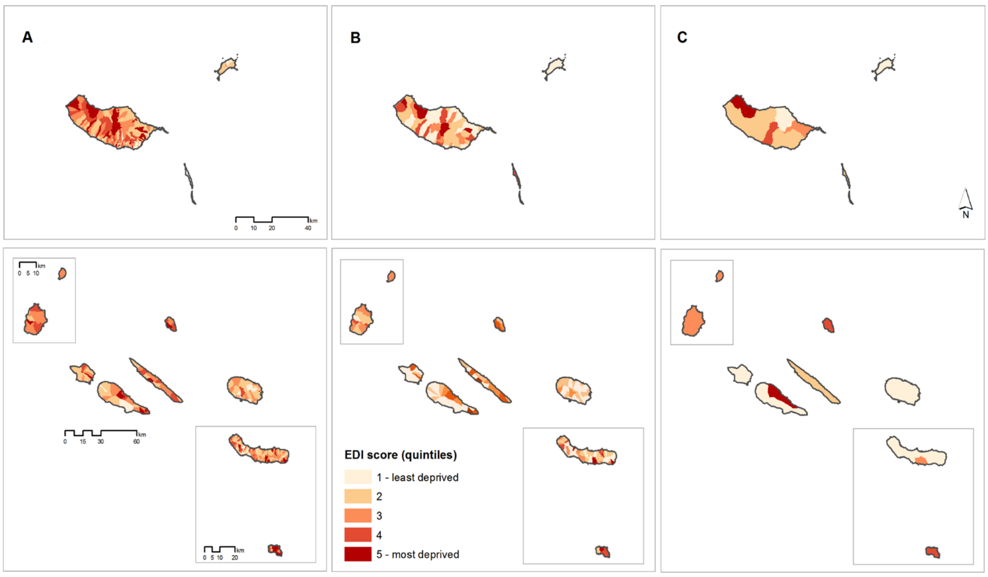

Figure 2. Spatial distribution of the European Deprivation Index in Madeira and Azores Archipelagos. (A-census block groups; B-parishes; C-municipalities)

considered those that were associated with this variable. The weights were attributed according to the role (association) each variable had in predicting individual deprivation. Most of available indicators are simply the unweighted sum of variables pragmatically chosen from the census; weighting is rare and usually justified by statistical criteria only.

Another advantage of the Portuguese EDI has to do with the fact that EU-SILC survey is conducted annually across all the European Member states. That guarantees EDI can be replicated over time, at least every ten years, when the census take place. The survey-based deprivation indexes of UK[28-31] follow a similar methodology as EDI but they cannot be replicated in other European countries. Developing comparable and replicable multivariate indexes will generate comparable and replicable study findings, which is indispensable for evidence-based public health decisions.

Moreover, the EDI is currently also available in four other countries from Western Europe, France, Italy, Spain and

England[35,41]. That will allow integrated studies, something particularly useful at the present time when scientific research is getting a cross-national extend due to the European financing channels. Hopefully, in the future other countries will follow the same methods and develop their own EDI.

In Portugal, where access to micro data is usually constrained, having a deprivation index that can be recomputed at different geographical aggregation levels is also a plus. For instance, mortality data cannot be disclosed for areas smaller than parishes or municipalities. So, any neighborhood-level index would be pointless. But, when using information from individual datasets (cohort studies, cross-sectional surveys), which allow obtaining the point location of each participant, using a local measure of deprivation is crucial.

Inevitably, the EDI has also a few limitations that deserve further discussion. Firstly, the choice of the variables to include in EDI depended greatly on the information available in the EU-SILC survey and in the census. The Portuguese EDI included a total of eight variables, which is less than the number of variables included, for instance, by our French counterparts (a total of ten)[41]. That can obviously impact the quality of the indicator. Another limitation of EDI is related to a widely discussed and controversial topic, the capability of a single deprivation index to discriminate rural and urban deprivation[42,43]. EU-SILC survey does not allow weighting on urban and rural areas, which could potentially affects its capability of measuring rural deprivation.

Conclusions

In sum, we propose an alternative deprivation index for Portuguese small areas, grounded on a solid theoretical framework, using both individual and aggregate variables and relying on a longitudinal Europe-wide survey that guarantee EDI can be replicated over the time and space. We have tried to be as explicit as possible so that any interest party could make the best use of this indicator. Hopefully, EDI will start being employed by social and medical researchers but also by regional planners, with the ultimate goal of better understanding the health inequalities not only in Portugal but also across Europe.

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4.3.1.2. Development of a measure of multiple physical environmental deprivation. After United Kingdom and New Zealand, Portugal (paper III)

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Development of a measure of multiple physical environmental deprivation. After United Kingdom and New Zealand, Portugal

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Background: Spatial inequalities in health have been identified, but the contribution of physical environment has been largely ignored. In Portugal, strong spatial differences in morbidity and mortality remain unexplained. Based on previous United Kingdom (UK) and New Zealand (NZ) research, we aimed to develop a Portuguese measure of multiple environmental deprivation (PT-MEDIx) to assist in understanding spatial inequalities in health. **Methods**: PT-MEDIx was built at municipality level in four stages: (i) identify health-relevant environmental factors; (ii) acquire datasets about selected environmental factors and calculate municipality-level measures using Geographical Information Systems; (iii) test associations between selected environmental factors and mortality using negative binomial models, adjusting for age, sex, socioeconomic deprivation and interactions and (iv) construct a summary measure and assess its association with mortality. **Results**: We included five dimensions of the physical environment: air pollution, climate, drinking water quality, green space availability and industry proximity. PT-MEDIx score ranged from −1 (least environmental deprivation) to +4 (most) and depicted a clear spatial pattern: least deprived municipalities in the depopulated rural areas and most deprived in urban and industrial settings. Comparing with those in the intermediate category of environment deprivation, less deprived municipalities showed lower mortality rate ratios (MRRs) and vice versa: MRRs for all-cause mortality were 0.962 (95% confidence interval: 0.934–0.991) and 1.209 (1.086–1.344), in the least and most deprived municipalities, respectively, and for cancer, 0.957 (0.911–1.006) and 1.345 (1.123–1.598). **Conclusions**: The methods used to create UK and NZ indexes have good transferability to Portugal. MEDIx might contribute to untangle the complex pathways that link health, socioeconomic and physical environment.

Introduction

Spatial inequalities in health and health-related behaviours have been identified worldwide.[1] Reducing health inequalities is currently a political priority,[2] yet spatial inequalities in health are widening rather than narrowing.[3] However, individual-level characteristics and area-level socioeconomic differentials are far from being the whole explanation for them.

Physical environment might be a key determinant of the spatial distribution of health and disease.[4] However, it has been often ignored by research on inequalities. Where it has been included, the focus has tended to be on harmful factors (e.g. pollution and climate extremes) ignoring the beneficial ones (e.g. green space and mild climate). Also, researchers have typically analyzed single exposures, ignoring the fact that pathogenic exposures rarely occur in isolation, and have mostly considered acute effects, overlooking the potential chronic effects.[5] We hypothesize that a wide range of harmful and beneficial factors, interacting with each other and with socioeconomic, cultural and individual characteristics, might shape the geographies of health.

Recently, researchers from United Kingdom (UK) and New Zealand (NZ) looked at the implications of physical environmental for spatial inequalities in health. They followed the principles used to build well-known socioeconomic deprivation indexes—England,[6] Scotland,[7] Wales[8] and Northern Ireland[9] indices of multiple deprivation, which recently started to integrate variables of the physical environment such as air pollution, as well as Carstairs[10] and Townsend.[11] The outcome was the creation of the Multiple Environmental Deprivation Indexes (MEDIx) specific to UK and to NZ.[12–17] These indexes, together with socioeconomic deprivation, contributed to a better understanding of spatial inequalities in health within these countries. Indeed growing evidence suggests the effect of socioeconomic and environmental deprivation on health inequalities cannot be detached; they need to be studied within an 'environmental justice' framework to assess whether most socioeconomically deprived populations are exposed to harmful physical environments and vice versa.[18] Environmental justice can be defined as the fair treatment and meaningful involvement of all people, regardless their demographic and socioeconomic profile, with respect to the development, implementation and enforcement of environmental laws, regulations and policies.[19]

In Portugal, studies on health inequalities are sparse. Even so, several-fold differences in mortality and morbidity have been identified.[20–23] Nevertheless, the strong regional differences in diseases, such as coronary heart disease, remain partially unexplained, possibly due to the restricted diversity (mostly economic and health resources) of the explanatory variables that have been considered.[20]

On the basis of the research from the UK and NZ, we aimed to develop a Portuguese measure of multiple environmental deprivation (PT-MEDIx). Our aim was also to assess how the choice of the environmental factors, datasets and methods of analysis should be adapted to the Portuguese idiosyncrasies without compromising comparability. This article describes how the PT-MEDIx was created, and how it is associated with risk of mortality in Portugal.

Methods

The development of PT-MEDIx followed the precedent set by the UK and NZ indexes and therefore had four stages[12–17]:

(1) Identify health-relevant environmental factors for Portugal.
(2) Acquire and prepare datasets of such environmental factors.
(3) Test associations between the environmental factors and health.
(4) Construct the summary measure and assess its associations with health.

The term 'environmental deprivation' refers to physical environment that surrounds population and that includes external physical (e.g. climate), chemical (e.g. pollution) and biological (e.g. greenness) factors; social and cultural factors were excluded.[13]

Stage 1—identify health-relevant environmental factors for Portugal

To define whether an environmental factor was relevant for health, we used two criteria: (i) robust scientific evidence of a beneficial or harmful effect and (ii) at least 10% of the Portuguese population should be exposed to health impacting levels. This threshold was developed and adopted by the UK- and NZ-MEDIx research.[13,16] While rather arbitrary, it nonetheless ensures that the included factors affect a reasonable proportion of the national population. In the UK work, for example, the threshold led to the exclusion of radon exposure, which affects a small and spatially restricted proportion of the UK population.

To identify which factors were related to health, an extensive literature review was conducted on key bibliographic databases—'Pubmed' and 'WebOfKnowledge', for studies about:

– Climate
– Traffic air pollution
– Industrial pollution
– Drinking water quality
– Ionizing radiation: ultraviolet B radiation (UVB) and radon
– Green space
– Noise.

We also sought Portuguese and Southern European-specific studies of the relationships between these factors and health.

Exposure to non-ionizing radiation (extremely low and radio frequencies) is rare in Portugal (<0.5% of the population), so we did not review the literature on that topic. We also excluded contaminated land, as datasets describing its distribution were unavailable.

A table summarizing the epidemiological evidence about the health impact of each factor is provided as Supplementary Material (see Supplementary table S1). Full reviews were written and are available from Centre for Research on Environment Society and Health and Institute of Public Health, University of Porto websites.[24,25]

Stage 2—acquire and process datasets about the selected environmental factors

Portugal mainland territory is divided into 278 municipalities (average population = 36 000), which are subdivided in parishes (average population = 2500). The studies from UK and NZ were grounded in small geographic units: census area statistics wards (UK) and census area units (NZ). PT-MEDIx was constructed at municipality level because (i) parish boundaries change frequently; (ii) socio-demographic data at parish level are available only for census years and (iii) mortality and health data are difficult to obtain at parish level due to confidentiality and, when accessible, they lack completeness and quality. To ensure our results were not biased by this decision, we replicated the study at parish level as far as possible. Key results remained unchanged.

We included only Portuguese-wide datasets, likely to be regularly updated, complete and of good quality. No country-wide dataset on noise exposure was found, leading to its exclusion. Similarly, no complete dataset on the duration of heat waves or cold spells was found. However, the distribution of the duration of extreme temperature events follows the geographical pattern of mean temperatures.[26] Available data on indoor radon exposure had outdated an inadequate geographical coverage, therefore was not considered. As almost all datasets were available for 2006, we centred our study around that year.

Table 1 describes the datasets used and the measures derived from them. Using a Geographical Information System, ArcGIS 10.2, we rendered each environmental dataset to municipalities. We calculated population-weighted means at municipality level to account for the unequal distribution of residents. An Europe-wide 1-km population grid[30] was used to calculate population-weighted exposures of air pollution, nitrates in private water supplies, climate and UVB.

Data for trihalomethanes (THM) in drinking water were already provided by municipality. To assess proximity to industries, a 3 km buffer (median radius found in the reviewed literature) around each facility was created and then intersected with the population grid to access the proportion of population within each municipality living within that radius. Population exposure to higher than recommended levels of THM was 8.3% but, being cautious, we included THM in our measure. Further, although nitrates in public water supplies are almost absent, high nitrate levels are quite common in private water sources in densely populated areas with intensive agriculture. In 2011, 13% of the Portuguese households were not connected to public water supplies, but population often uses both private and public supplies, meaning a much higher proportion of people using private water sources and, consequently, exposed to its contaminants. Again, cautiously, nitrates in private water supplies were included in analysis.

Stage 3—test associations between selected environmental factors and health

To validate the previous selection, a preliminary analysis was conducted to confirm whether each of the environmental factors had expected associations with health outcomes, after adjustment for sex, age and socioeconomic deprivation. Environmental factors were included in the development of the PT-MEDIx if significantly associated with mortality. When they were strongly and significantly correlated, the factor with the strongest effect and most scientifically documented was kept in the summary measure.

Mortality data were obtained from the Statistics Portugal for a 5-year period (2006–2010) and computed by municipality, gender, age group (0–14, 15–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, ≥85) and cause of death [all-cause mortality excluding external causes (ICD-9 codes < 800, ICD-10 A00-R99), cardiovascular disease (CVD, ICD-9 390-459, ICD-10 I00-I99) and cancer (ICD-9 140-239, ICD-10 C00-D48)]. Sex and age-specific population counts for the same geographic units and periods were also acquired. As no multiple index of socioeconomic deprivation is available for Portugal, we used the proportion of population of each municipality receiving social-financial support in 2011 (last census) as a measure of socioeconomic deprivation.[17]

To account for the large variance in the death counts, negative binomial regression models were used to model the association between each environmental factor and mortality, after adjusting for socioeconomic deprivation, age and sex structure of the population and interaction between socioeconomic and

Table 1 Description of the datasets and municipality-level measures derived for the selected environmental factors

Environmental factor	Source	Description	Processing	Municipality-level measure	Year(s)
Air pollution	Airbase from European Environment Agency (EEA)[27]	Annual averages of: particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and carbon monoxide (CO)	EEA provide 10 km grids for PM_{10}, $PM_{2.5}$ and O_3, exclusively; 10 km grids for the remaining pollutants were derived from station data (also from EEA) and interpolated using kriging.	Population-weighted mean of each pollutant	2006
Green space	Coordination of Information on the Environment (CORINE) Land Cover Data[28,29]	Map of land cover (44 classes)	Twenty-seven classes corresponding to green areas were selected.	Total percentage of green space	2006
Climate	Portuguese Institute for Ocean and Atmosphere (Instituto Português do Mar e da Atmosfera, IPMA) and Spanish Meteorology Agency (Agencia Estatal de Meteorología, AEMET)	Climatological averages by station ($n = 74$): annual mean (year), warmest month (July), maximum and coldest month (January) minimum temperatures (°C)	1 km grids for each temperature were derived using kriging as interpolation method	Population-weighted mean of each climate variable	1970–2000
UVB Index	Portuguese Institute for Ocean and Atmosphere (IPMA, Instituto Português do Mar e da Atmosfera)	Average UVB index (unitless) Geographical Information System grid with a spatial resolution of 0.5° (~50 km) obtained by satellite images (clean sky)	–	Population-weighted mean	2003–2012
Industrial facilities	European Pollutant Emission Register (EPER)	Location of the waste management sites, mineral and chemical manufacture, metal production and processing facilities and combustion installations.	–	Proportion of population living within 3 km of some facility	2008
Drinking water quality	Public water supplies Regulator Institute of Water and Waste (Instituto Regulador de Águas e Resíduos, IRAR)	Annual median by municipality For each parameter: magnesium (Mg), calcium (Ca), nitrates (NO_3^-), aluminum (Al), arsenic (As), manganese (Mn), lead (Pb) and THM	–	Median of each parameter	2011
	Private water supplies (ground water from wells, boreholes and springs) Water Resources Information National System (Sistema Nacional de Informação de Recursos Hídricos, SNIRH).	Median by station for nitrates (NO_3^-)	1 km grids were derived using kriging as interpolation method		1997–2012

environmental deprivation (PT-MEDIx). The age- and sex-specific population of each municipality was included as exposed population (model offset). Results were expressed as mortality rate ratios (MRRs) and corresponding 95% confidence intervals (CIs).

Sulphur dioxide (SO_2) was uncorrelated with all mortality causes (MRR ~1), so that it was not included in PT-MEDIx. The variables of temperature were highly correlated; therefore, we only kept mean temperature. The same issue applied to particulate matter (PM_{10}, $PM_{2.5}$) and ozone (O_3). We opted to retain PM_{10}, since reported effects on health are stronger and better studied.

Additionally, UVB and water hardness were excluded. The UVB was positively associated with each of the measures of mortality (e.g. MRR = 1.130, 95% CI: 1.105–1.155 for all-cause mortality); however, there is no biologic plausibility for an harmful effect of UVB on causes of death other than skin cancer (an infrequent cancer in Portugal[31]), especially because the UVB has little spatial variability in Portugal. Measures of water hardness presented a positive but weak relationship with CVD (MRR = 1.006, 95% CI: 1.005–1.007 for magnesium and MRR = 1.003, 95% CI: 1.002–1.003 for calcium). Lacking biologic plausibility for a 'harmful' effect of water hardness in CVD, those variables were excluded.

Stage 4—construct the summary measure and assess its association with health

To quantify the degree of multiple environmental deprivation in each municipality, we developed a single measure combining information on each environmental factor.

Ideally, we would have assessed whether each factor exceeded a health-relevant threshold within a municipality. However, the literature shows that there are no robust and consistent thresholds for any of them. We therefore identified municipalities as being exposed to a health-relevant amount of each factor, if situated in the highest quintile of that factor. Municipalities in the highest quintile of exposure received a score of +1 for harmful factors and −1 for beneficial factors. Harmful air pollution was defined as the highest quintile of 'any' of the air pollutants. The PT-MEDIx of each municipality resulted from the sum of these scores and ranged from −1 (least environmental deprivation) to +4 (most). No weighting of the factors was undertaken because there is no robust evidence by which to rank them according to health impact.

Once PT-MEDIx was built, negative binomial regression models were again used to estimate the association with mortality, adjusting for age-group, sex, socioeconomic deprivation and interaction between socio-economic deprivation and PT-MEDIx. To rule out the possibility that regression analysis might have led to spatially correlated errors, we mapped the residuals and calculated the Moran's I statistic; only a small and non-significant spatial autocorrelation in the residuals was observed.

We conducted several sensitivity analyses to insure that results were not solely determined by the method used or the time period of the mortality data. These were:

(i) Trying multiple ways of computing the index.

  (a) A uniquely positive index where all variables are considered detrimental, that is, a municipality in the lowest quintile of green space availability punctuated +1.
  (b) An index based on extreme values of each factor, that is, municipalities in the 95th percentile of exposure received a punctuation of +1 and −1, for harmful and beneficial factors, respectively.

(ii) Estimating the association between PT-MEDIx and health using mortality data of 2003–2005.

Results remained substantively unchanged despite the changes.

All models were run in R version 3.0.1 using 'mgcv' package.[32]

Results

Spatial distribution of PT-MEDIx

Figure 1 depicts the spatial distribution of PT-MEDIx scores across Portugal. The highest scores were found in the large urban centres, the metropolitan areas of Porto and Lisboa and surroundings, the industrial area of Aveiro (coastline south of Porto) and the southern Alentejo and Algarve regions (figure 1). In contrast, the depopulated, rural and mountainous inner north and centre registered the lowest environmental deprivation. No clear latitudinal/longitudinal trend was observed in PT-MEDIx spatial distribution.

One third of the municipalities were classified into the intermediate category, having neither high exposure to harmful nor to beneficial factors. Twelve percent were placed in the least environmentally deprived group (depopulated and mountainous areas where 3% of the population lives), whereas only 5% were placed in the category of highest environmental deprivation (with 20% of the population).

Table 2 lists median values of the included environmental factors according to PT-MEDIx score—as it rises, an increase in the median exposure to the different factors is observed.

PT-MEDIx and health

For all-cause and cancer mortality, the more environmentally deprived municipalities showed significantly higher MRRs (using intermediate level of environmental deprivation as reference), even after adjustment for confounders (table 3). Associations with CVD were positive but did not reach statistical significance.

Comparing with those in the intermediate category, less environmentally deprived municipalities showed lower MRRs and more deprived municipalities showed higher MRRs: MRRs for all-cause mortality were 0.962 (95% CI: 0.934–0.991) and 1.209 (95% CI: 1.086–1.344), in the least and most deprived municipalities respectively, and for cancer, 0.957 (95% CI: 0.911–1.006) and 1.345 (95% CI: 1.123–1.598). Putting it in absolute terms, the most environmentally deprived municipalities had 6300 extra deaths per year when compared with the reference category (MEDIx = 0). For cancer, the dose–response relationship is particularly evident: the highest MRRs were found in areas with a score of +3 or +4.

Discussion

The UK/NZ approach to calculating an MEDIx was successfully transferred to Portugal. We identified factors in the physical environment that were related to population's health in Portugal, which, combined, resulted in an ordinal index which we used to classify municipalities according to the level of multiple environmental deprivation. Significant and plausible associations with all-cause, cardiovascular and cancer mortality were found even after adjusting for demographic and socioeconomic confounders. Associations with cancer were stronger and seemed to follow a dose-response pattern.

By creating PT-MEDIx, we answered international calls for more evidence-based, ready-to-use and understandable multivariate indexes.[33] Multivariate indexes are valuable tools for policy makers and other stakeholders. They contribute to a better understanding and monitoring of multidimensional phenomena. When aspects of environment are assessed and regulated as individual components, it is likely that the possibility of improving health via intervention is reduced. We run the risk of fixing one problem, ignorant of the fact that many others exist in the same location. The understanding that there are multiple aspects of environmental deprivation, which might require more than one policy intervention, is therefore vital. Such indexes also help to identify populations which are at relatively greater or lower risk.

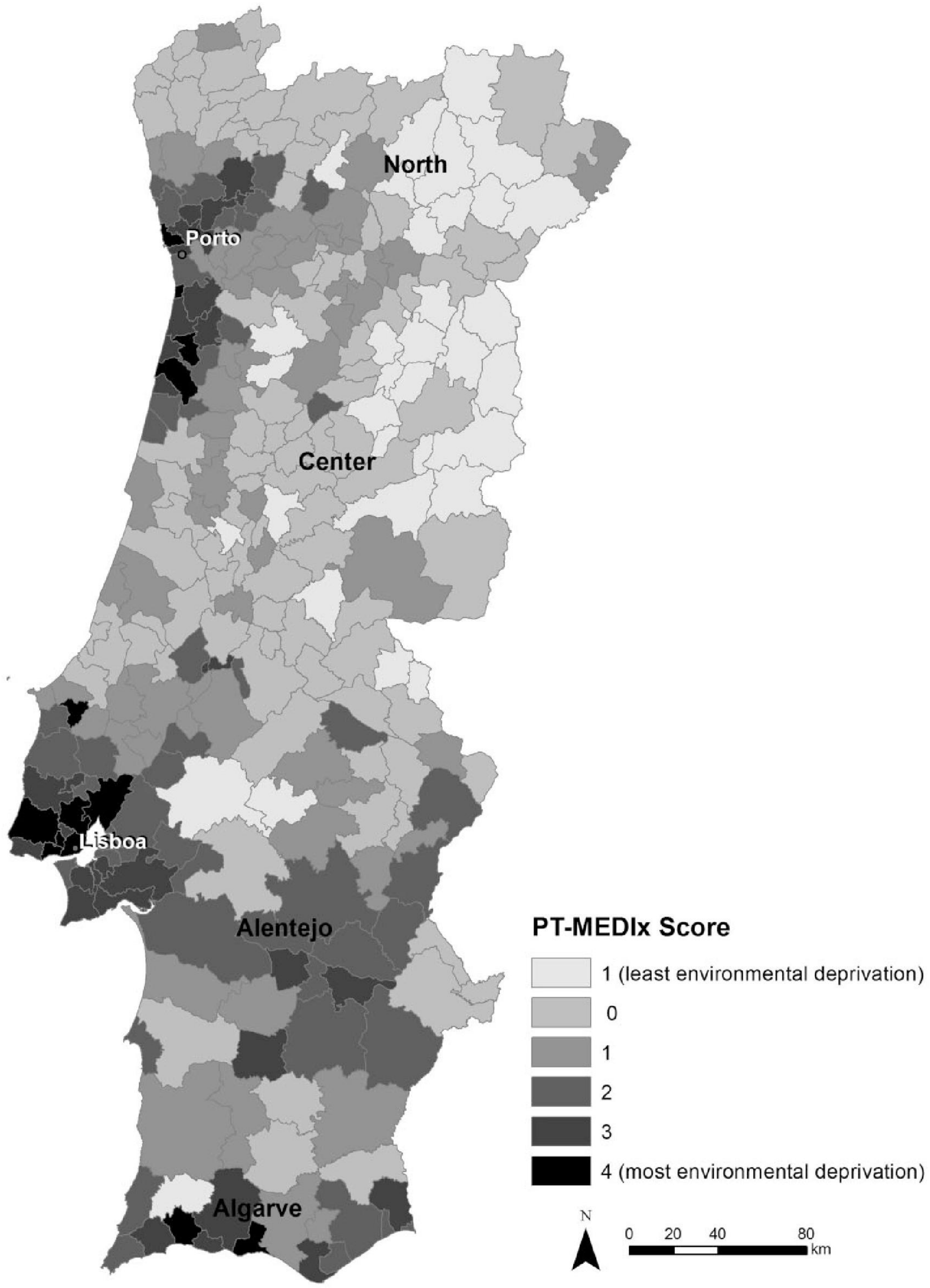

Figure 1 Spatial distribution of PT-MEDIx scores across Portugal

The major strength of this study lies on the fact that we succeeded to collect a large amount of data and developed a comprehensive environmental deprivation index for Portugal which can now be compared with UK/NZ indexes. Moreover, as with the development of MEDIx in the UK/NZ, we used clear methods, allowing its reproduction in different contexts. The sensitivity analyses help reassure that the results are not unduly driven by the methods selected—the choice of the geographical unit, the temporal reference of mortality data and the way environmental factors were combined, did not meaningfully alter the key results. Moreover, we saw that environmental deprivation represents a crucial health determinant, capable of causing an annual excess of 6000 deaths.

Although our methodology was deliberately similar to the UK/NZ indexes, the datasets, variables and final results are distinct (see Supplementary table S2). For UK-MEDIx, eight variables (SO_2, nitrogen dioxide, PM_{10}, carbon monoxide, average temperature, UVB, green space and industries) were considered, in NZ-MEDIx four (PM_{10}, average temperature, UVB and green space) and in

Table 2 Characteristics of the MEDIx scores—median values of the environmental factors for each PT-MEDIx score

	PT-MEDIx score					
	−1 (least environmental deprivation)	**0**	**+1**	**+2**	**+3**	**+4 (most environmental deprivation)**
No. of municipalities (%)	34 (12.2)	93 (33.5)	60 (21.6)	45(16.2)	33(11.9)	13(4.7)
Population (2006) (%)	337 085 (3.4)	1 645 962 (16.4)	2 067 310 (20.6)	1 723 042 (17.2)	2 234 933 (22.3)	2 017 506 (20.1)
Environmental factors						
PM_{10}[a]	12.97	15.78	17.78	18.85	21.67	22.91
NO_2[a]	18.64	20.03	22.01	23.08	26.97	29.19
CO[a]	168.13	165.65	192.04	191.70	232.89	246.34
Mean temperature (°C)[b]	13.07	15.05	15.33	15.73	15.77	16.01
Industry proximity (%)[c]	0.00	0.73	3.99	7.79	62.51	65.54
Green space (%)[d]	99.25	98.06	96.34	95.01	78.26	73.08
THM[e]	5.00	5.00	9.28	19.20	32.30	43.00
NO_3^-[f]	7.00	8.00	11.00	24.00	27.00	29.00
Deprivation[g]	2.95	3.73	4.07	4.46	4.63	4.52

a: Annual average ($\mu g/m^3$).
b: Annual average temperature (1970–2000).
c: Proportion of municipality's population living within 3 km of an industrial facility.
d: Proportion of the municipality's area covered with green space.
e: THM annual median ($\mu g/m^3$).
f: Annual median (mg/m^3).
g: Proportion of population of each municipality receiving social-financial support in 2011.

Table 3 MRRs (and corresponding 95% CIs) for the association between PT-MEDIx and mortality, adjusted for covariates (age, sex, socioeconomic deprivation[a] and interaction between socioeconomic deprivation and PT-MEDIx)

	All-cause	**Cardiovascular disease**	**Cancer**
PT-MEDIx			
−1 (least deprived)	0.962 (0.934-0.991)**	0.924 (0.880-0.969)**	*0.957 (0.911-1.006)*
0	1.000	1.000	1.000
+1	*1.024 (0.979-1.072)*	1.115 (1.038-1.198)**	*1.005 (0.930-1.084)*
+2	*1.012 (0.970-1.056)*	*1.032 (0.962-1.106)*	1.147 (1.078-1.220)***
+3	1.199 (1.083-1.327)***	*1.106 (0.929-1.312)*	1.312 (1.100-1.552)**
4 (most deprived)	1.209 (1.086-1.344)***	*1.071 (0.892-1.281)*	1.345 (1.123-1.598)***
$-2 \times$ log likelihood	108 130.3	70 747.0	72 202.9
Likelihood ratio test (*P* value)[b]	<0.001	<0.001	<0.001

*0.01 < *P* value < 0.05.
**0.001 < *P* value < 0.01.
****P* < 0.001.
a: Proportion of population of each municipality receiving social-financial support in 2011.
b: Chi-square test to compare the final model (with PT-MEDIx) and the incomplete model (without PT-MEDIx).

PT-MEDIx, eight. UVB is unrelated with Portuguese mortality, contrasting with a strong protection found in UK and NZ, probably due to the smaller latitudinal extent of Portugal. Temperature had a positive association with mortality in Portugal, whereas in NZ and in UK, the association went in the opposite direction. This was not surprising as in Portugal temperature rarely reaches life-threatening lows, but heat extremes are frequent and unquestionably harmful.[34,35] Contrasting with UK and NZ, where no measure of drinking water quality was available, THM and nitrates showed strong and significant associations with cancer mortality. If NZ-MEDIx has a balance of detrimental/beneficial factors, in PT-MEDIx we included considerably more detrimental factors, with just one beneficial characteristic (green space). This contributed to the differing ranges of the indexes. Moreover, we were not able to follow NZ's strategy of including health-related behaviours as confounders due to data unavailability. As in NZ, we found a higher proportion of the country's population living in the most environmentally deprived areas than was found in UK. This was not surprising. The internal regions of Portugal, the least environmentally deprived, experienced massive depopulation since the 1980s. The UK has not experienced such large population shifts in recent history.

As in the UK/NZ analyses, in Portugal, the effect of environmental deprivation on health was progressive and moderate.[16,17] Still, areas with disadvantaged physical environment experienced significantly higher risk of mortality.

This study had several limitations. Because of data unavailability, we could not include environmental factors such as noise and radon exposure. Results might change with their inclusion. Although we tried to include accurate and contemporary datasets, the presence of inaccuracies remains a possibility. Establishing a causal relationship between PT-MEDIx and health was also not possible from this cross-sectional study design.

There are three particular problems with cross-sectional data and design in this study. (i) PT-MEDIx is a snapshot of the environmental characteristics of each municipality in a single time period, which might not correspond to the environmental characteristics to which the population was exposed during lifetime. (ii) We assumed place of the residence as the area where health-relevant exposures occur, but individuals might have spent much time in another area. (iii)

We could not adjust our analysis for other crucial health factors, such as physical activity, smoking or obesity. However, these factors are linked to socioeconomic deprivation and control for deprivation may have reduced their confounding influence. A further weakness is that, as in the UK/NZ analyses, we treated all factors as equal contributors to environmental deprivation. This might be unrealistic, but without robust evidence, any weighting would be arbitrary. Finally, we chose municipalities as geographical units for practical reasons. It is highly likely that these units do not capture very well environmental exposures with high spatial variability, such as green space or pollution. The unavoidable integration of gridded and areal data might also have obscured the true spatial distribution of the environmental exposures. Gridded data had greater resolution than polygons (municipalities); the only exception was UVB, whose grid cell size was larger than the municipality polygons; however, because of the small spatial variability of UVB, matching it with the polygons does not represent a major problem.

In conclusion, this work resulted in an evidence-based and understandable indicator of environmental deprivation for a southern European nation. This measure could help to comprehend the poorly understood spatial inequalities in health in Portugal; to untangle the complex pathway that links individual-characteristics, socioeconomic and physical environment and to identify vulnerable populations and address their specific problems. PT-MEDIx could be used by both academics and policy makers. Despite being moderate, associations between environmental deprivation and health cannot be ignored, as they affect a large number of people. After being built for three distinct countries, we encourage other teams to develop similar environmental deprivation indexes and test their validity and utility in explaining health inequalities. Such work will enhance debate about the role of physical environment in health inequalities.

Supplementary data

Supplementary data are available at *EURPUB* online.

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Conflicts of interest: None declared.

Key points

- Spatial inequalities in health have been identified but the contribution of physical environment has been largely ignored.
- We developed an evidence-based and understandable indicator of environmental deprivation for Portugal, including for the first time water quality parameters.
- Significant and plausible associations between this indicator and all-cause and cancer mortality were found.
- Hopefully, this measure could assist to better understand spatial inequalities in health; to untangle the complex pathway that links individual characteristics, socioeconomic and physical environment and to identify vulnerable populations and address their specific problems.

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4.3.1.3. Access to Healthcare Index (AHI)

The access to healthcare resources is a vital aspect too, especially at older ages due to the heavy burden of chronic diseases and to higher susceptibility to infections. The likelihood of surviving beyond certain age is certainly affected by the use of healthcare resources (165). Healthcare availability and accessibility are two domains of access to healthcare (345). The first concept, availability, refers to whether or not the existing health services and goods meet clients' needs. The second, accessibility, refers to whether or not the location of supply is in line with the location of clients.

To derivate the Access to Healthcare Index (AHI) for older population we started by retrieving all variables that express healthcare availability and accessibility. These variables were obtained from two different data sources and basically express three distinct domains: long-term care and social support facilities (e.g. day-care centres, nursing homes, and home care), access and activities of healthcare facilities (e.g. hospitals, pharmacies, primary healthcare centres), and health professionals (e.g. medical doctors, dentists, nurses). Variables and indicators were obtained at municipality level, for the year 2001 (whenever possible), for Continental Portugal. From that pool of variables, those with too many missing/censored values and those with too many zeros were discharged. Then we calculated rates, ratios and proportions that would express the population exposure to those variables. Variables were subsequently characterized and transformed to become more normally distributed. Afterwards, bivariate correlations were computed to identify variables which were excessively correlated, which were also discharged. Finally, principal component analysis (PCA) was run to derivate a summary measure expressing access to health care for older population in each municipality. The steps for the construction of the AHI are fully described in the present section.

Step 1: Acquiring of data on healthcare availability and accessibility, assessing completeness, and selecting variables

In Tables 2-4 they are listed the datasets on healthcare availability and accessibility that were extracted and evaluated. Datasets either come from Hospitals and Primary Care Surveys under the responsibility of Statistics Portugal (INE, Instituto Nacional de Estatística) (346, 347), Carta Social produced by the Ministry of Solidarity, Employment and Social Security (348), or PORDATA® (349). Data on the geographical accessibility to hospitals, was calculated using a Geographical Information System (GIS), with the location of the public hospitals (n=106, 7 maternity and children's hospitals were discharged) in 2001 as point locations, the parish centroids as destinations, and the 2001 ESRI (Environmental Systems Research Institute) country's street network . Distances were then averaged by municipality and weighted to the resident population of the parish, that way accounting for the number of potential healthcare users. No variables existed on the quality and/costs of healthcare at a regional level, two important domains of the access to healthcare services (345).

Table 2. Datasets about long term care and social support facilities.

ID*	Description	Year	No. areas with data	No. areas with zeros	Missing	Source
1	Capacity (no. of users) of the occupational centres per 1000 people	2008	153	125	0	Carta Social
2	Capacity (no. of users) of the residential care per 1000 people	2008	95	183	0	Carta Social
3	**Capacity (no. of users) of the day-care centres per 1000 older people**	**2008**	**271**	**7**	**0**	**Carta Social**
4	**Capacity (no. of users) of the nursing homes per 1000 older people**	**2008**	**278**	**0**	**0**	**Carta Social**
5	**Capacity (no. of users) of the home care per 1000 older people**	**2008**	**278**	**0**	**0**	**Carta Social**
6	**Capacity (no. of users) of all social equipment per 1000 older people**	**2008**	**278**	**0**	**0**	**Carta Social**

*dataset identifier; in bold are selected datasets

Table 3. Datasets about geographical accessibility and activities of healthcare facilities (hospitals and primary care centers).

ID*	Description	Year	No. areas with data	No. areas with zeros	Missing	Source
7	Calls in the urgencies from the hospitals	1998	49	192	37	INE
8	Calls in permanent/prolonged care service in primary care centres	2001	223	55	0	INE
9	Beds (capacity) in all health facilities (/1000 inhab.)	2001	115	125	38	INE
10	Beds in the primary care centers	2001	63	215	0	INE
11	Beds in the hospitals	2001	56	183	39	INE
12	Primary care centres according to the existence of basic urgency and permanent/prolonged care (total;yes;no)	2001	278;223;74	0;55;204	0	INE
13	Primary care centres according to the existence of home care (total;yes;no)	2001	278;277;3	0;1;275	0	INE
14	**Primary care centres according to the existence of internment (total;yes;no)**	**2001**	**278;63;216**	**0;215;62**	**0**	**INE**
15	**Primary care centres extensions**	**2001**	**259**	**19**	**0**	**INE**
16	Consultations in the outpatient visits of the hospitals according to medical specialty	2001	55	185	38	INE
17	Consultations in the health facilities per inhabitant	2001	240	0	38	INE
18	Consultations in the primary care centres according to medical specialty	2001	278	0	0	INE
19	**Population weighted mean distance to public hospitals (km)**	**2001**	**278**	**0**	**0**	**GIS calculation**
20	**Population weighted mean distance to public hospitals (minutes)**	**2001**	**278**	**0**	**0**	**GIS calculation**
21	**Pharmacies and mobile pharmacy posts according to type of unit**	**2001**	**278**	**0**	**0**	**INE**

22	Pharmacies and mobile pharmacy posts (/1000 inhab.)	2001	278	0	0	INE
23	**Hospitals according to the institutional nature (total;official;private)**	**2001**	**95;72;44**	**183;206;234**	**0**	**INE**
24	Hospitals according to the institutional nature (total;general;specialized)	2001	71;68;8	207;210;270	30	PORDATA
25	Hospital admissions in the primary care centres	2001	63	215	0	INE
26	Hospital admissions in the hospitals	2001	57	183	38	INE
27	Hospital admissions in all healthcare facilities (/1000 inhab.)	2001	115	125	38	INE
28	Legal abortions in the hospitals	2001	9	231	38	INE
29	Medium and large surgeries per day in the hospitals	2001	50	189	39	INE
30	Medium and large surgeries per day in all healthcare facilities	2001	51	189	38	INE
31	Deliveries in the public hospitals according to the type of delivery	2001	44	234	0	INE
32	Deliveries in the hospitals according to the type of delivery	2001	28	211	39	INE
33	Length of stay in the primary care centres (Day)	2001	63	215	0	INE
34	Length of stay in the hospitals (Days)	2001	57	183	38	INE
35	Surgery rooms	2001	51	189	38	INE
36	Occupation rate in the healthcare facilities (%)	2001	115	125	38	INE

*dataset identifier; in bold are selected datasets; INE - Insituto Nacional de Estatística (Statistics Portugal); GIS – Geographic Information System

Table 4. Datasets about the healthcare professionals.

ID*	Description	Year	No. areas with data	No. areas with zeros	Missing	Source
37	Nurses by workplace (/1000 inhab.)	2001	275	3	0	INE
38	**Nurses by place of work and gender**	**2002**	**278**	**0**	**0**	**INE**
39	Workshop pharmacists by workplace	2001	275	3	0	INE
40	**Pharmacists by workplace and gender**	**2002**	**277**	**1**	**0**	**INE**
41	**Dentists by place of residence and gender**	**2002**	**211**	**67**	**0**	**INE**
42	Specialized medical doctors by place of residence and medical specialty	2002	263	15	0	INE
43	**Medical doctors by place of residence and gender**	**2002**	**277**	**1**	**0**	**INE**
44	Non-specialized medical doctors by place of residence	2002	265	13	0	INE
45	Medical doctors by place of residence (/1000 inhab.)	2002	277	1	0	INE
46	Pharmacy professionals by workplace	2002	272	6	0	INE
47	**Health professionals in primary care centres according to category**	**2001**	**278**	**0**	**0**	**INE**
48	**Health professionals in public hospitals according to category**	**2001**	**71**	**207**	**0**	**INE**
49	Health professionals in hospitals according to category	2001	56	183	39	INE

**dataset identifier; in bold are selected datasets; INE - Instituto Nacional de Estatística (Statistics Portugal)*

For this initial set of 49 datasets we have disregarded those with a significant number of missing values and zero values, and duplicated datasets. Most variables about the characteristics of the hospitals and about their performance had to be excluded because of the large number of missing and censured values. Accordingly, we used only information from 16 datasets, translated into 16 variables, most of which were transformed into population exposure indicators (rates/ratios):

1. Capacity (no. users) of the day-care centres (/1000 older inhab.) in 2008 (dataset ID 3)
2. Capacity (no. users) of the nursing homes (/1000 older inhab.) in 2008 (ID 4)

3. Capacity (no. users) of the home care (/1000 older inhab.) in 2008 (ID 5)
4. Capacity (no. users) of all social equipment (/1000 older inhab.) in 2008 (ID 6)
5. Primary care centres and extensions (/1000 km2) in 2001 (ID 14, 15)
6. Population-weighted mean distance (km) to the public hospitals in 2001 (ID 19)
7. Population-weighted mean distance (minutes) to the public hospitals in 2001 (ID 20)
8. Pharmacies and mobile pharmacy posts (/1000 km2) in 2001 (ID 21)
9. Hospitals (/100,000 inhab.) in 2001 (ID 23)
10. Nurses by place of work (/1000 inhab.) in 2002 (ID 38)
11. Nurses in the National Health Service, NHS, (/1000 inhab.) in 2001 (ID 47, 48)
12. Pharmacists by place of work (/1000 inhab.) in 2002 (ID 40)
13. Dentists by place of residence (/1000 inhab.) in 2002 (ID 41)
14. Medical doctors by place of residence (/1000 inhab.) in 2002 (ID 43)
15. Medical doctors in the NHS (/1000 inhab.) in 2001 (ID 47, 48)
16. Diagnostic and therapeutic technicians in the NHS (/1000 inhab.) in 2001(ID 47, 48)

Step 2: Descriptive statistics and pre-treatment of the variables

Descriptive statistics – measures of centrality and dispersion - and histograms were used to characterize the previously selected variables, and to identify those with skewed distributions. Whenever variables are not normally distributed, scientific literature strongly emphasizes the need to

Table 5. Summary statistics of the sixteen access to healthcare variables selected.

Variable	Mean (standard deviation)	Range (minimum-maximum)	Transformation	Decision
1. Capacity of the day-care centres (/1000 older inhab.)	42.1 (33.1)	0.0-166.7	$\sqrt{X}$	Kept
2. Capacity of the nursing homes (/1000 older inhab.)	50.2 (32.6)	9.0-232.8	$\ln X$	Kept
3. Capacity of the home care (/1000 older inhab.)	62.3 (38.4)	5.9-321.7	$\ln X$	Kept
4. Capacity of all social equipment (/1000 older inhab.)	154.6 (82.7)	30.5-518.5	$\ln X$	Kept
5. Primary care centres and extensions (/1000 km^2)	41.5 (64.1)	1.6-614.5	$\ln X$	Kept
6. Population weighted mean distance (km) to the public hospitals	25.0 (17.5)	0.2-87.9	$\ln X$	Kept
7. Population weighted mean distance (minutes) to the public hospitals	20.3 (14.2)	0.1-75.3	$\ln X$	Kept
8. Pharmacies and mobile pharmacy posts (/1000 km^2)	82.6 (316.9)	0.8-3935.2	$\ln X$	Kept
9. Hospitals (/100,000 inhab.)	1.3 (3.0)	0.0-29.4	$\ln X$	Eliminated
10. Nurses by place of work (/1000 inhab.)	2.1 (2.6)	0.04-20.5	$\ln X$	Kept
11. Nurses in the national health service (NHS) (/1000 inhab.)	1.8 (2.0)	0.1-18.3	$\ln X$	Kept
12. Pharmacists by place of work (/1000 inhab.)	0.5 (0.3)	0.0-2.9	$\ln X$	Kept
13. Dentists by place of residence (/1000 inhab.)	0.2 (0.2)	0.0-1.5	$\sqrt{X}$	Kept
14. Medical doctors by place of residence (/1000 inhab.)	1.5 (1.9)	0.0-19.5	$\ln X$	Kept
15. Medical doctors in the NHS (/1000 inhab.)	1.2 (1.2)	0.2-11.9	$\ln X$ *and* $\sqrt{X}$	Eliminated
16. Diagnostic and therapeutic technicians in the NHS (/1000 inhab.)	0.3 (0.4)	0.0-3.7	$\sqrt{X}$	Eliminated

perform variable transformation before running PCA (350-352). Principal component analysis is sensitive to the relative scaling of the original variables.

All variables were highly skewed, showing high and positive values of skewness. Therefore, all variables were either log-transformed (ln X) or power transformed (√X, square rooted, more suitable for small numbers) (350). The two municipalities with no resident medical doctors or pharmacists received a value between 0 and 1, so that we could proceed to the log-transformation. In certain cases, variables were recalculated (for instance, some rates were changed as per 100 000 instead of per 1000 inhabitants) so that log transformation did not create variables with both positive and negative values, which could difficult the interpretation of the results.

Due to the excessive amount of zero values, the variables hospitals per inhabitants and diagnostic and therapeutic technicians in the NHS were removed; these were strongly correlated with other variables we kept (distance to hospitals and with variables about other health professionals, respectively). The variable “medical doctors in the NHS” was also eliminated due to its highly skewed distribution (despite successive transformations) besides measuring, essentially, the same as medical doctors by place of residence (Table 5).

Step 3: Investigate excessive collinearity and selection of variables for principal component analysis

In this step we generated a correlation matrix to assess which variables were excessively correlated. Whenever pairs of variables were highly correlated (>0.800) and were related to the same domain, only one (that with a value of skewness closer to zero) was kept. As expected, the variables on the geographical accessibility to the hospitals, distances to hospitals in minutes and in kilometres, were highly correlated; distance in kilometres was discharged. To facilitate posterior interpretation, the remaining variable “Population weighted mean distance (minutes) to the public hospitals” was re-calculated so that it expresses (as all other variables) healthcare accessibility and not the opposite. The logarithm of the inverse function was employed for that purpose.

There were two variables on the availability of nurses, which were also much related and, for the reasons above mentioned, the variable about the presence of nurses from the NHS was discharged. The summary variable about the availability of all social equipment was highly correlated with the three variables that measured the availability of each specific social equipment, being for this reason discharged as well.

In summary, for further analysis 10 variables were considered: capacity of the day-care centres (/1000 older inhab., square rooted); capacity of the nursing homes (/1000 older inhab., log-transformed); capacity of the home care (/1000 older inhab., log-transformed); population weighted mean distance to public hospitals (/100 minutes, logarithm of an inverse); primary care centres and extensions (/1000 km2, log-transformed); pharmacies and mobile pharmacy posts (/10,000 km2, log-transformed); medical doctors by place of residence (/100,000 inhab., log-transformed); nurses by place of work (/100,000 inhab., log-transformed); dentists by place of residence (/1000 inhab., square rooted); and pharmacists by place of work (/100,000 inhab., log-transformed).

Step 4: Principal component analysis and score calculation

Principal component analysis is a useful technique for transforming a large number of variables in a dataset into a smaller and more coherent set of linearly uncorrelated (orthogonal) components (353). Each component is a linear weighted combination of the initial variables. The number of principal components is less than or equal to the number of original variables. The components are defined so that the first principal component accounts for the largest possible variance, and each succeeding component accounts for the maximum variation that is not accounted for the previous.

To assess whether the dataset was adequate to PCA, the Kaiser-Olkin test was computed; a statistically significant ($p<0.001$) test values of 0.816 was obtained, confirming adequacy of the dataset to PCA. To select the number of components to keep the interpretability criteria was used. It is the most important criterion for solving the "number of components" problem. It implies interpreting the substantive meaning of the retained components and verifying that this interpretation makes sense in terms of what is known about the constructs under investigation (354, 355): 1) do the variables that load on a certain component share the same meaning?; 2) on the contrary, variables that load on different components measure different constructs?; 3) does the rotated factor pattern demonstrate a simple structure, where each variable clearly belongs to just one component? We also confronted our solution with the percent variation explained (≥70%), scree test, and eigenvalue criteria (≥1).

Accordingly, three components were retained, which together explained 72.1% of the variance. Varimax rotation was employed to identify the variables belonging to each component (Table 6). The first component included variables about the geographical accessibility and availability of hospitals, primary care centres, and pharmacies; the second, on the availability of health professionals; and the third about the capacity of long-term and social support services.

Table 6. Rotated component matrix from Principal Component Analysis of access to healthcare variables.

Variable	Component		
	1	2	3
Capacity of the daycare centres (square rooted)	0.020	-0.011	**0.821**
Capacity of the nursing homes (log-transformed)	-0.302	-0.036	**0.694**
Capacity of the home care (log-transformed)	-0.338	-0.091	**0.711**
Inverse distance to the public hospitals (log-transformed)	**0.658**	0.473	-0.363
Primary care centres and extensions (log-transformed)	**0.905**	0.104	-0.210
Pharmacies and mobile pharmacy posts (log-transformed)	**0.831**	0.241	-0.410
Medical doctors by place of residence (log-transformed)	0.801	**0.814**	-0.205
Nurses by place of work (log-transformed)	0.066	**0.851**	0.165
Dentists by place of residence (square rooted)	0.200	**0.660**	-0.448
Pharmacists by place of work (log-transformed)	0.528	**0.510**	0.210

*at bold are the variables that load more on each component

Then, for each municipality, i, we have multiplied the component score by its weight, the percentage of variation explained (equation 1). The final score expressed the level of access to healthcare for older population in each municipality.

$$\text{AHI score}_i = 0.25340 \times \text{1st component}_i + 0.23857 \times \text{2nd Component}_i + 0.22924 \times \text{3rd component}_i$$
(equation 1)

The score varied from -1.10 to +1.63. After normalization it was categorized into classes based on standard deviations to the overall mean, customized so that classes included a balanced number of areas. For instance, considering five categories, the first category comprised values lower than -0.84; the second category values between -0.84 and -0.25; the third values between -0.25 and

0.25; the fourth values between 0.25 and 0.84 and the fifth values higher than 0.84. Each category is expected to comprise 20% of the observations, assuming a normal distribution.

Figure 9 shows the spatial distribution of the AHI for older population, using the before mentioned categories. The urban areas (namely, the district capitals and surroundings) generally registered the highest scores of access, together with several municipalities of the Centre of Portugal. The lower scores were found in the Inner North and in several areas of Southern Portugal (mainly, in the districts of Beja and Faro). Although using a distinct approach and focusing in specialized healthcare, Santana also found large regional iniquities in their accessibility to older people (356).

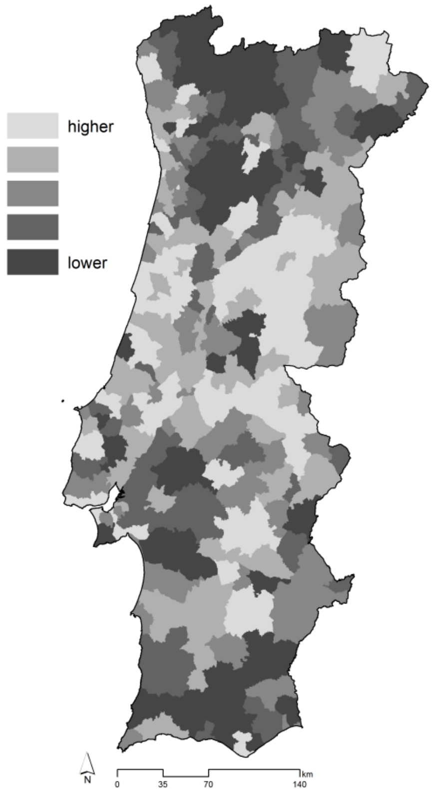

Figure 9. Spatial distribution of the Access to Healthcare Index (AHI) for older population.

5. Results

5.1. Chapter introduction

This chapter reports the results of the six non-methodological articles of this thesis. The manuscripts of each article are included. The first four manuscripts (corresponding to papers I, IV, V and VI) answer the first and third objectives of this thesis, that is, to characterize the spatial inequalities in old-age survival in Europe, Portugal and Porto municipality, and to understand the role of different contextual determinants – socioeconomic, physical environmental and healthcare – in shaping those patterns. We start from a wider scope, Europe, where we identify critical areas in terms of survival (very high/very low) and estimate the country-specific impact of socioeconomic deprivation. We then move to the Portuguese and Porto contexts to look at the impact of other correlates of old-age survival, besides socioeconomic circumstances: physical environment (biogeophysical and built) and access to healthcare.

The next two articles address another public health concern, active ageing, and refer to the fourth objective of the present thesis – test whether or not the social, economic and physical characteristics of the residential environment affect the PA levels of older adults within Porto municipality. The first study relied on baseline information from EPIPorto cohort and was mostly focused on physical attributes of the neighbourhoods, whereas the later was based on information from the second evaluation of the same cohort and added to the list of neighbourhood PA correlates a more social one: the presence of crime.

Results are analysed as a whole in the discussion part of this thesis.

5.2. Where do people live longer and shorter lives? An ecological study of old-age survival across 4404 small areas from 18 European countries (paper I)

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Where do people live longer and shorter lives? An ecological study of old-age survival across 4404 small areas from 18 European countries

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ABSTRACT

Background Further increases in life expectancy in high-income countries depend to a large extent on advances in old-age survival. We aimed to characterise the spatial distribution of old-age survival across small areas of Europe, and to identify areas with significantly high or low survivorship.

Methods This study incorporated 4404 small areas from 18 European countries. We used a 10-year survival rate to express the proportion of population aged 75–84 years who reached 85–94 years of age (beyond average life expectancy). This metric was calculated for each gender using decennial census data (1991, 2001 and 2011) at small geographical areas. To address problems associated with small areas, rates were smoothed using a Bayesian spatial model. Excursion sets were defined to identify areas with significantly high (>95th centile) and low (<5th) survival.

Results In 2011, on average, 47.1% (range: 22.5–71.5) of the female population aged 75–84 years had reached 85–94 years of age, compared to 34.2% (16.4–49.6) of the males. These figures, however, hide important and time-persistent spatial inequalities. Higher survival rates were concentrated in northern Spain, Andorra and northeastern Italy, and in the south and west of France. Lower survival was found in parts of the UK, Scandinavia and the Netherlands, and in some areas of southern Europe. Within these regions, we detected areas with significantly high and low old-age survival.

Conclusions Clear and persistent spatial inequalities in old-age survival exist, suggesting that European social unity is still to be accomplished. These inequalities could arise from a myriad of population health determinants (eg, poverty, unhealthy lifestyles), which merit further study.

INTRODUCTION

Life expectancy is regulated by two connected mechanisms[1 2]—postponed death and increase in longevity or maximal age at death. The first reflects the decline in premature mortality, whereas the second reflects an increase in old-age survival.[3] Both contribute to the progress in life expectancy but, currently, the increase in old-age survival seems to play a greater role.[1 2]

Old-age survival is shaped by individual genetics and behaviours, environmental exposures, and by interactions between them,[4–6] which can lead to significant geographic differences. Studies have found an unusual number of long-lived people in small areas of Italy,[7–10] Greece,[11] Spain,[12] China[13] and Japan.[14] The presence of these geographic differentials suggests that old-age survival could be changeable, and thus it could be further extended. However, a comprehensive, continent-wide picture of the spatial inequalities in longevity is still lacking.

Studying the spatial distribution of old-age survival across small areas is challenging. The calculation of life expectancy, and its components, at such a fine geographical scale is limited by the need for disclosure control of mortality data. So, usually, the only possible way of addressing this issue is through the use of population census data.

Since the presence of a high proportion of long-lived people in a certain area might simply reflect patterns of migration and/or birth rates, some specific indicators of longevity have been developed.[8–10] These indicators 'track' the older population through time and space to estimate how many have survived beyond the average lifespan, resulting in a survival rate. Yet, the study of intercensal population changes across small areas continues to pose important problems related to boundary changes, procedures and random fluctuations. These difficulties might explain the small number of studies about spatial inequalities in longevity.

The present study aims to investigate the presence of spatial inequalities in old-age survival in Europe. We will characterise the spatial distribution of old-age survival across small areas of Europe and then identify areas where old-age survival is particularly high/low. We have focused on the European Union to guarantee a degree of epidemiological and demographic homogeneity.

METHODS

Study area

All European Union countries, including dependencies and insular territories, were eligible for the study (n=28). Greece, Cyprus, Germany, Ireland and recent Eastern Europe members were excluded because official publications lack information about the population counts of older age groups in these countries (n=15).

To ensure spatial continuity, non-member states which share borders with European Union countries, and had available data, were also eligible. Therefore, Norway, Switzerland, Andorra, Liechtenstein and San Marino were also included (n=5).

Our study area therefore covers 18 countries, which contain 4404 small areas, spread across 2

295 698 km^2, with an overall population of 313 296 725 inhabitants.

Longevity indicator, population and spatial data

On the basis of previous studies,[8–10] we defined old-age survival as a 10-year survival rate indicating the proportion of the population aged 75–84 years in a census year who survived to 85–94 years of age by gender and area. Survival was calculated within two periods—1991–2001 and 2001–2011.

This approach allows us to minimise the unknown effects of migration and birth rates on area populations. In areas where migration rates are high and birth rates are low, the use of total population (all age groups) as a denominator is inappropriate, as it would artificially inflate the survival rate. Selecting the population aged 75–84 years as the denominator is more suitable since migration rates at an advanced age tend to be relatively low.[15] We considered the long-lived population as those who survived to 85–94 years of age because, first, they have surpassed the average lifespan and, second, population counts after 94 years of age are usually aggregated in a single group.

Population counts were obtained from the Statistic Offices of each country, by 5-year age groups (75–79, 80–84, 85–89 and 90–94), gender, census year (1991, 2001 and 2011) and the smallest geographical area available. Details about the population data are presented as online supplementary material 1. Digital base maps with geographical boundaries were also acquired.

Often, in between censuses, there are substantial changes to the boundaries of the geographical areas. Consequently, we had to merge areas, and corresponding population counts, so that it was possible to compare population counts in consistent areas throughout the three censuses. In addition, to make areas as comparable as possible, in some countries we had to use areas from an upper aggregation level. The summary characteristics of the 4404 geographical areas are shown in table 1.

Statistical analysis

To account for spatial autocorrelation and the small number problem, we considered a model with an intrinsically conditional autoregressive plus an unstructured term, which smooths the survival rates eliminating extremes in areas with a small population and reduces high local variance.[16] The inference was performed under the Bayesian paradigm using the Integrated Nested Laplace Approximation (INLA) approach.[17]

Our objective is to study the 10-year survival rate r_{kit}

$$r_{kit} = \frac{y_{kit}}{n_{kit-10}} \qquad (1)$$

where k=1, 2, denotes gender, i=1,…,4404, denotes area, and t=2001, 2011, denotes the census year. The variable y represents the population aged 85–94 years and n represents the population aged 75–84 years 10 years before.

In France, the decennial censuses took place in 1990 and 1999, so there is an interval of only 9 years in the first period considered. As a result, we used the clustered/clumped Binomial model to model yearly mortality probability. To apply this approach, we had to consider the deaths as an outcome and fit a model for the yearly probability of death. This probability is assumed to be constant between the two censuses.

The linear predictor in the model (η_{kit}) is a function of an intercept (β_0), gender (β_1), census year (β_2), a spatially structured random effect (s) and an unstructured random effect one (u). Details about the models considered are available as online supplementary material 2.

The selected model is in the form

$$\eta_{kit} = \beta 0 + \beta 1 \times \text{gender} + \beta 2 \times \text{year} + s_{ki} + u_{kit} \qquad (2)$$

where the spatially structured effect varies over the areas and is shared between the different genders, and the unstructured effect varies over gender, areas and periods.

Table 1 Summary characteristics of the geographical areas of each included country

Country	Area (km^2)	Total population (2011)	Number of geographical areas*	Mean population by geographical area	Name
Andorra	468	75 655	7	10 808	parròquia
Austria	83 879	8 401 940	99	84 868	Bezirk
Belgium	30 528	11 035 948	589	18 737	commune
Denmark	43 094	5 560 628	99	56 168	kommune
Finland	338 145	5 401 267	320	16 879	kunta
France	543 965	62 446 966	330	189 233	arrondissement
Italy	301 230	59 433 744	638	93 156	distretto sanitario
Liechtenstein	160	36 475	1	36 475	country
Luxembourg	2586	512 353	12	42 696	canton
Malta	316	414 989	1	414 989	country
The Netherlands	41 528	16 655 799	418	39 846	gemeente
Norway	385 155	4 920 305	428	11 496	kommune
Portugal	92 090	10 562 178	308	34 293	município
San Marino	61	33 376	1	33 376	country
Spain	504 030	46 818 625	337	138 928	comarca
Sweden	449 964	9 482 855	284	33 390	kommun
Switzerland	41 285	7 954 662	147	54 113	Bezirk/district/distretto
UK	244 829	63 750 770	385	165 586	local authority
Total	2 295 698	313 296 725	4404	71 139	

*Note that, to compare population counts throughout the three decennial censuses, we had to combine some geographical areas; consequently, the number of geographical areas included in the study does not fully correspond to the official number of geographical areas in each country in 2011.

Excursions

Map visualisation alone cannot be used to identify extremes of very high/low old-age survival as large areas are more noticeable than smaller ones. In addition, maps do not reveal the uncertainty of the estimates, which are greater in areas with fewer inhabitants. These were important issues for our study because it included areas with large variations in size.

A method based on excursion sets was recently developed,[18] and it is implemented in the R package 'excursions. This method uses the posterior joint distribution computed from INLA and computes the probability of extremes taking into account the dependence structure. It allows the accurate identification of areas where the survival probability is greater/smaller than a threshold. Year-specific and gender-specific thresholds were established. Survival was considered to be particularly high or low if it was situated in the tails of the distribution—above percentile 95 and below percentile 5, respectively. A significance level of 0.05 was adopted.

RESULTS

Overall pattern

On average, in 2001, the proportion of the male population aged 75–84 years which had survived to 85–94 years was 27.1% (range: 16.6–48.2), whereas among women the survival rate was 39.9% (25.4–67.1). In 2011, rates of survival had significantly increased to 34.2% (16.4–49.6) among men and 47.1% (22.5–71.5) among women.

The spatial distribution of the 10-year survival rates is shown in figures 1A and 2A. In 2001, areas with higher survival were mostly found in the northern half of Spain, northern Italy, Switzerland, west of France, south of England, Norway and Sweden, Sardinia, and in the Canary Islands. Low longevity was typically found in northern UK, southern Spain, Portugal, the France–Belgium border, and in several areas of Scandinavia. In 2011, the overall pattern remained but the areas of France with higher survival rates have expanded.

Areas with high/low old-age survival

Men

In 2001, we identified 27 areas of high male survival (rates above 33.7%) and 31 areas of low survival (below 20.8%) (figure 1B). Areas of high male survival were mainly located in Spain (near Madrid and Salamanca, among others), Andorra and Switzerland (Geneva). Areas of low survival were mostly found in the industrial regions of the UK (Glasgow, Manchester and Liverpool), in the London region and, in France, in northern mining and industrial districts, and Bretagne.

In 2011, we detected 49 and 24 areas of high (above 41.1%) and low (below 27.1%) survival, respectively. Joining the aforementioned areas of northern Spain and Andorra, areas of high male survival spread through southern and western France. Low survival areas persisted in industrial regions of the UK and London, and retained a now residual presence in the France–Belgium border, with incursions in the Netherlands (Amsterdam and South Limburg) and Denmark (Copenhagen).

Women

In 2001, the number of areas with high (above 48.4%) and low (below 32.4%) female survival was 45 and 35, respectively (figure 2B). Their spatial distribution reassembles that observed for men. High survival areas were found in northern Spain (namely around Madrid) and in northeastern Italy (Emilia–Romagna and Venetia). Areas of low survival, once more, predominated in the UK (London and industrial areas), and in the mining and industrial districts of the France–Belgium border, but were also found in southern Spain and Italy (Naples and Sicily).

In 2011, there were 102 and 50 areas with high (above 56.1%) and low (below 39.0%) survival, respectively. As happened among men, high survival areas expanded in western and southern France. The high survival areas in northern Spain were maintained, whereas in northeastern Italy they were greatly reduced. Low survival areas persisted in the UK (London and industrial areas), southern Spain and, to a more limited extent, in the France–Belgium border, and, as among men, in the Netherlands (Amsterdam) and Denmark (Copenhagen).

The complete list of the areas of high and low survival is provided as online supplementary material 3.

The proportion of the country population residing in areas of low and high old-age survival is presented in table 2. These results demonstrate that, in the UK, there are a large number of areas of low survival which hold a considerable amount of the population: in 2011, 18.2% of the national female population and 6.8% of the males resided in these areas. Table 2 also indicates the favourable position of Spain and Andorra (in 2001) and the great expansion of old-age survival in France from 2001 to 2011.

Some hidden patterns were revealed as well. In the northern European countries, Denmark and the Netherlands, areas of low survival, hardly seen in figures 1 and 2, hold about 10% and 5% of the national population, respectively, in 2011. Belgium shows a mixed pattern, where scattered areas of high and low survival coexist—some of the latter located in the ancient mining districts near the French border. In Switzerland, a few areas of high survival were consistently identified.

DISCUSSION

In this study, we have found clear spatial inequalities in old-age survival across 4404 areas in 18 European countries. These patterns mostly persisted throughout the 20-year period under analysis. We observed areas of higher survival rates concentrated in northern Spain, northeastern Italy and, lately, in the south and west of France. In contrast, low survival was found in parts of the UK, Scandinavia and the Netherlands, and in a few scattered areas of some southern European countries. Within these regions, we have found groups of areas with remarkably high/low old-age survival.

A myriad of factors can account for the spatial inequalities in old-age survival; a complex network of factors of different natures affects population health over the time, briefly summarised in figure 3.

Old-age survival is strongly determined by mortality after 85 years of age, which is mainly caused by cardiovascular disease (CVD), which accounts for 42% of the deaths in Europe.[19] Indeed, the current pattern of CVD mortality to some extent matches our pattern of survival[19 20]—lower rates are found in northern Spain and all over France. Temporal trends in CVD mortality may be responsible for the positive evolution in old-age survival that we observed.[21] Notably, they might account for the outstanding evolution in France, where CVD mortality keeps decreasing[21] despite its low starting point. Oddly, this progress in French old-age survival, also visible in routine statistical data, is poorly studied.

Individual risk factors such as smoking, blood pressure, diet, physical activity, alcohol intake and socioeconomic status are established risk factors for CVD at the individual level. Mediterranean dietary patterns (specifically low saturated fat

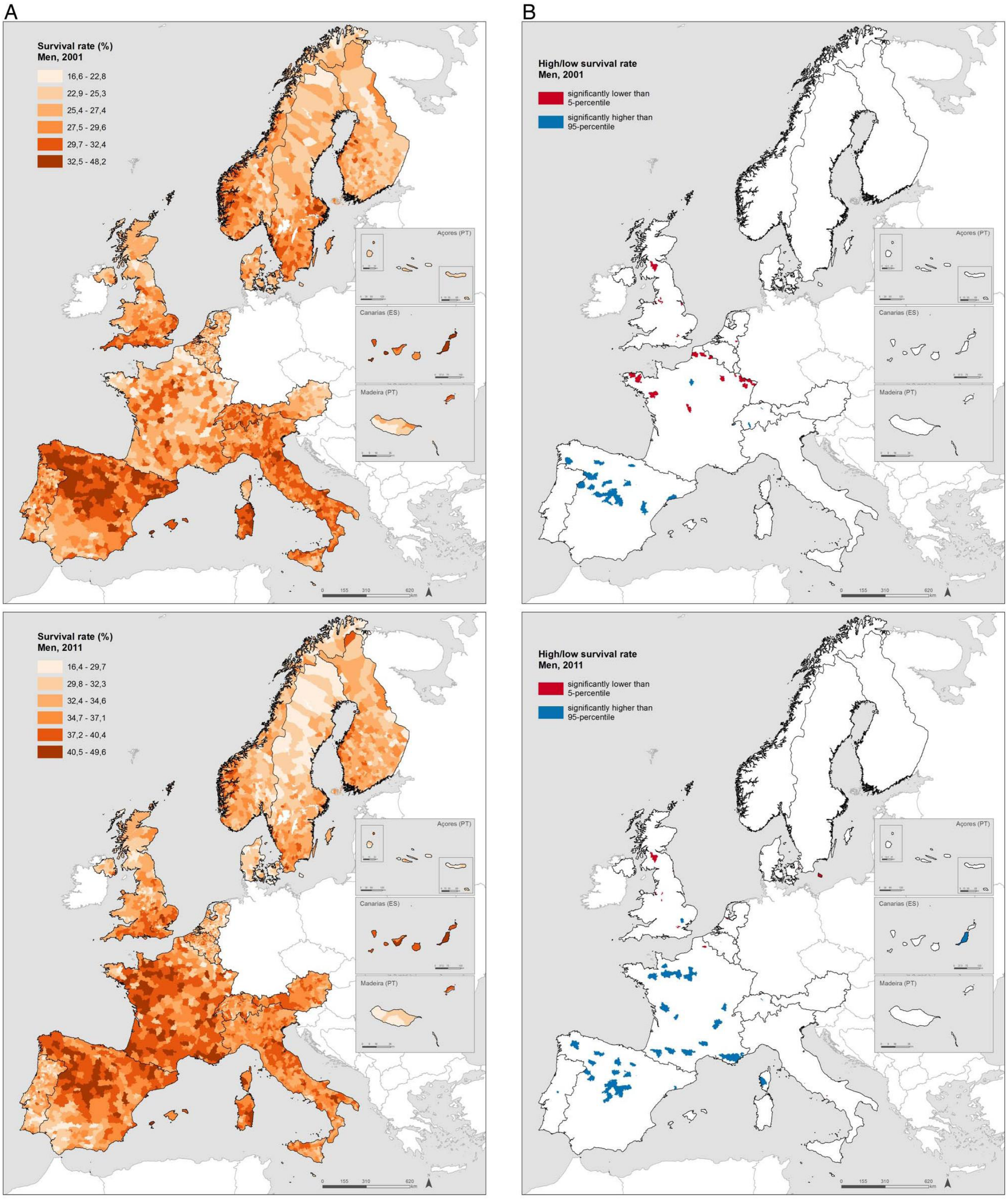

Figure 1 Spatial distribution of the 10-year survival rates across small areas of Europe in 2001 and 2011 (men). (A) Survival rates; (B) areas of high (above 95th centile) and low (below 5th centile) survival.

consumption), predominant in Southern Europe, seem to account for some (not all) of the spatial variation in CVD.[22 23] Smoking differentials must also play an important role. Yet, the lack of information on the spatial distribution of those factors across European areas does not allow further assessment.

It is unlikely that the same factors that explain individual differences explain all population/area differences as well.[23] Wider determinants such as social support,[22 24] the socio-economic[25–27] and physical environment,[28–30] and healthcare systems[31] might aid the explanation of the spatial inequalities in old-age survival (figure 3).

Although it is outside the scope of our study, it is possible to speculate about the potential role of socioeconomic deprivation in the geography of old-age survival. The gross domestic

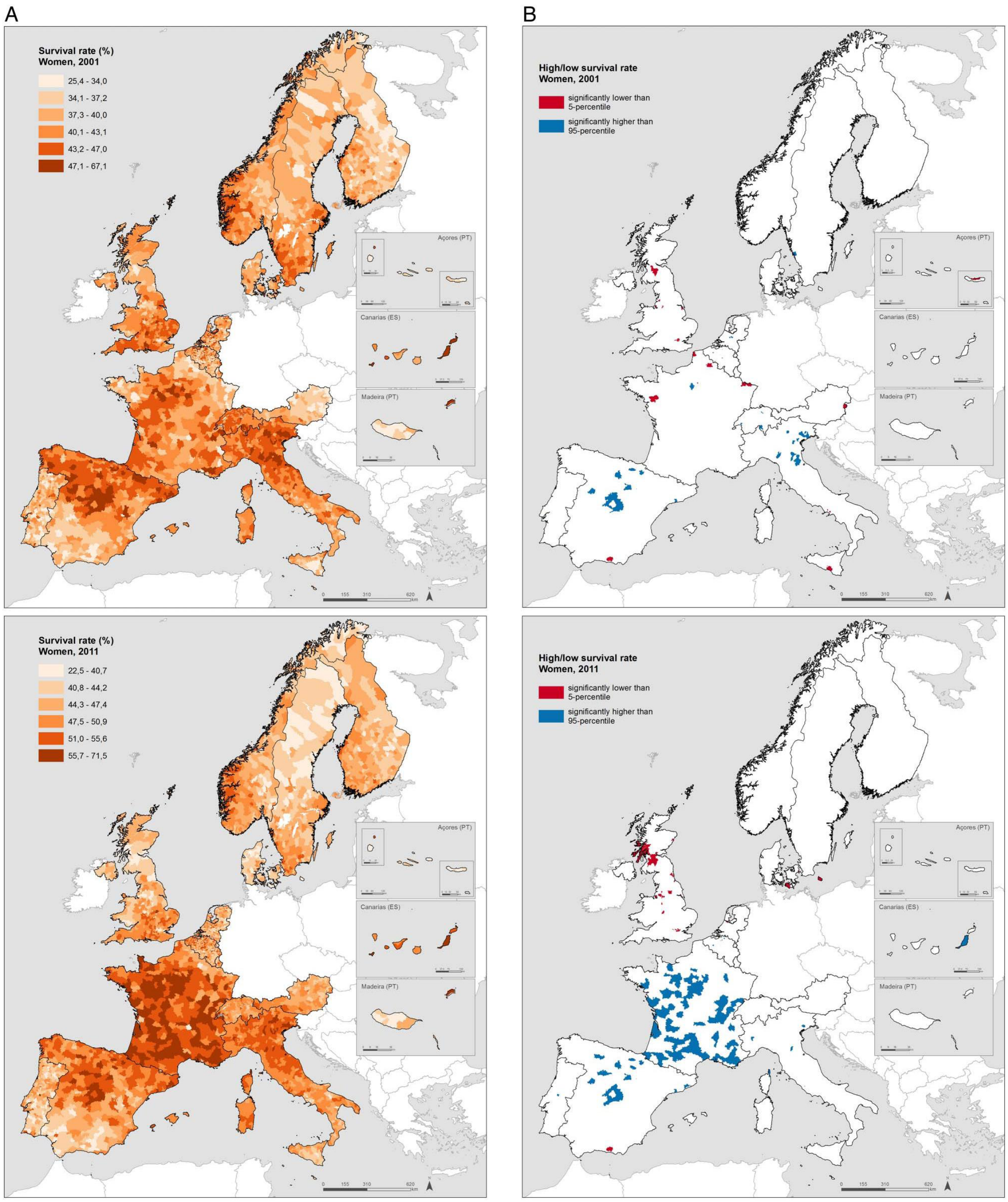

Figure 2 Spatial distribution of the 10-year survival rates across small areas of Europe in 2001 and 2011 (women). (A) Survival rates; (B) areas of high (above 95th centile) and low (below 5th centile) survival.

product (GDP) map of Europe, shown in online supplementary material 4,[32] might shed some light on the observed patterns. Portugal and south of Spain and Italy stand out as some of the most economically deprived regions and, coincidentally, these also exhibit relatively low old-age survival. The economically affluent regions of northern Spain, southern France and north-eastern Italy register large survival. Still, GDP distribution could not explain the low survival rates found in Denmark or the Netherlands.

Post-industrial regions such as West Central Scotland, the France–Belgium border or Merseyside (UK, near Liverpool) have been characterised by high poverty levels and an erosion of social cohesion.[33] Thanks to the use of a fine geographical scale, we were able to detect these areas, which remained

Table 2 Percentage of the country population living in areas of high and low survival rates by year and gender

	Men				Women			
	2001		2011		2001		2011	
Country	High survival*	Low survival†	High survival	Low survival	High survival	Low survival	High survival	Low survival
AD	54.3	NA	17.6	NA	55.5	NA	NA	NA
AU	NA	NA	NA	NA	NA	0.5	NA	NA
BE	NA	NA	0.3	0.4	0.7	0.6	0.6	0.4
CH	7.2	NA	1.3	NA	1.9	NA	NA	NA
DN	NA	NA	NA	10.4	NA	NA	NA	11.3
ES	7.1	NA	7.4	NA	5.9	0.1	9.8	0.2
FR	0.4	3.8	10.6	0.6	0.4	1.7	26.5	NA
IT	NA	NA	NA	0.2	2.5	0.6	0.4	NA
NL	NA	0.2	NA	5.3	0.5	NA	NA	5.0
PT	NA	NA	NA	NA	1.5	0.1	NA	NA
SE	0.3	NA	NA	NA	1.5	NA	NA	NA
UK	0.2	7.3	0.1	6.8	NA	5.3	NA	18.2

*Areas with 10-year survival rate above the 95th centile of the distribution in that year and gender.
†Areas with 10-year survival rate below the 5th centile of the distribution in that year and gender.
AD, Andorra; AU, Austria; BE, Belgium; CH, Switzerland; DN, Denmark; ES, Spain; FR, France; IT, Italy; NA, not applicable (no areas of high/low survival); NL, the Netherlands; PT, Portugal; SE, Sweden.

among those with the lowest old-age survival over time. We also found that survival rates in the urban areas of the Netherlands and Denmark are among the lowest in Europe. Interestingly, some studies have been published about the weak progress in the old-age life expectancy of these countries after the 1990s.[34] [35] The Netherlands could recently have reversed this pattern through an expansion of healthcare among the elderly.[36]

In summary, it is most likely that the observed patterns arise from a combination of two kinds of health determinants: poverty, which explains the low longevity found in areas like Portugal, southern Spain, southern Italy and post-industrial areas; and unhealthy lifestyles (eg, tobacco, diet), which might explain the presence of areas of low survival in affluent areas of Scandinavia or the Netherlands.

Limitations

The modifiable areal unit problem (MAUP) is an important challenge in our study. Demographic data are available for administrative areas, whose boundaries are arbitrarily chosen, and a different geographic arrangement could yield different results. Moreover, these areas tend to be rather large—containing great within-area variability in social phenomena. In our study, we could only address part of the MAUP by using the smallest geographical area possible, minimising within-area heterogeneity. Although we had tried to use areas as comparable as possible, in some countries the areas were substantially larger than in others. Our study is also grounded on the assumption that people have lived in the same area for 10 years; migration of the population aged 75 years or more has been shown to be relatively infrequent,[15] but it remains a possibility. While

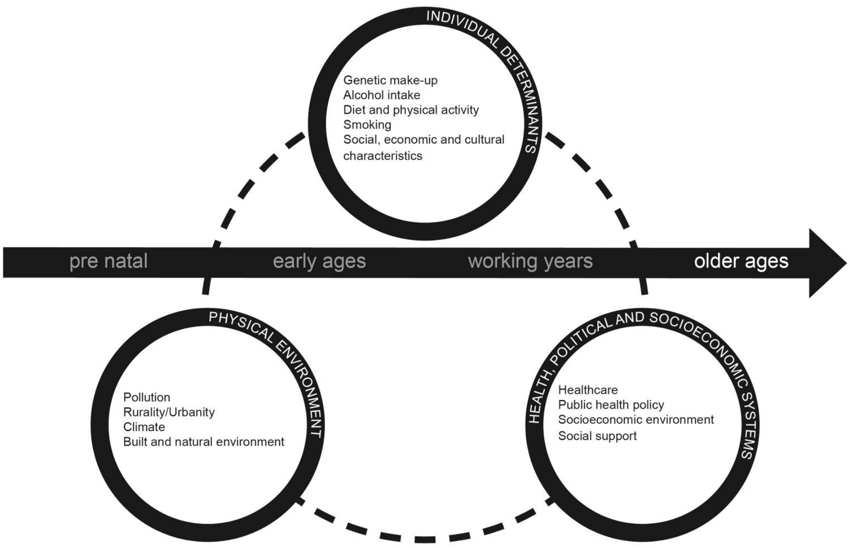

Figure 3 Overview of the possible factors implicated in the spatial distribution in old-age survival across small areas of Europe.

healthy and disability free life expectancy later in life are potent indicators of population health and quality of life, especially among the oldest (due to the increased burden of chronic and degenerative disease), our measure of old-age survival is not a direct measure of good health. Both healthy life years and life expectancy should be monitored,[37] as living longer and experiencing good health are independent and important political and personal targets.

Strengths

This is the first study to provide a broad picture of the spatial inequalities in old-age survival across small areas of Europe. Previous studies have focused mostly on life expectancy or mortality, and have used very coarse geographies,[19 20 38] combining very distinct social, economic and health realities. The delimitation of 'critical' areas is a small but important first step towards generating a public health response and identifying the underlying causes, poverty, healthcare or the physical environment. We have counteracted problems with the use of small areas with appropriate statistical methods that allow the removal of noisy patterns and support the accurate identification of areas with extremely high/low values. Moreover, we have produced a straightforward and understandable metric to estimate survival at advanced ages in small areas, which solely requires a time series of population census data. Although we cannot validate our measure, its overall pattern reassembles the one found for more complex measures such as mortality[20 38] and life expectancy[19] at the NUTS (Nomenclature of Territorial Units for Statistics) level, which supports the reliability and value of our indicator.

Our measure of old-age survival represents the ability of a population to survive beyond the average lifespan. It summarises the accumulation of the positive and negative effects of a network of health determinants over the life course and at older ages. Therefore, our study, and the background methodology, can help to characterise population health and mortality patterns, and monitor the space-time trends in old-age survival. Moreover, the diversity of spatial patterns can also teach us something about the potential contributors.

Tackling health inequalities is a top public health priority.[39] Our study has shown that there are stubborn inequalities in old age survivorship across Europe. The stubbornness of these inequalities indicates the (1) ineffectiveness of programmes to improve equity and/or (2) unconsciousness about the existence of such gaps. Future research should monitor healthy life expectancy later in life at the local level and address the roots of these inequalities.

What is already known on this subject

- In developed countries, premature mortality has plateaued at very low levels, and, consequently, old-age survival is now crucial to growth in life expectancy.
- Old-age survival is a good general indicator of population health and regional development.
- Spatial inequalities in health are entrenched in Europe, but so far no study has evaluated spatial inequalities in old-age survival across this continent.

What this study adds

- This is the first study to provide a broad picture of the spatial inequalities in old-age survival across Europe.
- We found clear and stubborn inequalities.
- In some areas, <30% of the 80-year-old population reaches 90 years of age, but in others the proportion of survivors goes well beyond 50%.
- Our findings suggest that it is urgent to rethink the previous population health programmes and to delineate new actions that can reach all European communities, but, specially, those that currently show the lowest survival rates at advanced ages.

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5.3. The association between socioeconomic deprivation and old-age survival in European small areas - a cross-national analysis (paper IV)

The association between socioeconomic deprivation and old-age survival in European small areas –a cross-national analysis.

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Abstract
Geographical differences in the spatial distribution of old-age survival exist in Europe, and might be attributed to socioeconomic deprivation. We determined the association between socioeconomic deprivation and old-age survival in Europe, and investigated whether it varies by country and gender.
Our study incorporated five countries (Portugal, Spain, France, Italy and England), which were divided into 1911 small areas. We derived a surrogate measure of life expectancy, a ten-year survival rate that expresses the proportion of population aged 75-84 years who reached 85-94 years old. To estimate associations (Relative Risks, RR, and 95% Credible Intervals, 95%CrI) Bayesian spatial models were used and a transnational measure of socioeconomic deprivation was included as covariate. Population attributable and preventable proportions were also calculated. Overall, there was a significant association between socioeconomic deprivation and old-age survival in both genders (Men in least deprived areas RR_1=1.075 (1.052-1.099); Women RR_1=1.157 (1.132-1.183)). In England that association was stronger (Men RR_1=1.232 (1.174-1.295); Women RR_1 =1.268 (1.209-1.331)), following clear dose-response relation. The same gradient was observable in Spain and Italy, whereas in France and Portugal the association with deprivation was considerably smaller. We estimated that the entire elimination of socioeconomic differences between areas would increase survival by more than 14%, and even a small improvement would represent a 3% increase in survival. In conclusion, socioeconomic deprivation was associated with survival among older adults, but the magnitude of the association varied considerably across countries. Reasons for such difference should be sought.
Key-words: socioeconomic factors; mortality; poverty; life expectancy; Geographic Information Systems.

Introduction

Health inequalities are entrenched in the European societies for centuries and do not show signs of reduction [1, 2] – in 2013 the life expectancy gap between EU member states was 9 years, slightly larger than the gap observed in the 1990s [3]. Whilst traditional risk factors are important to comprehend health inequalities observed at individual-level, between and within-country differences are mostly determined by unmeasured factors at ecological level [4-6], being socioeconomic deprivation one of the most impacting [7].

Currently, further increases in life expectancy depend to a large extent on reductions in old-age mortality [8]. This transforms survival rates at older ages into a key measure of population health. To date very few studies have examined the role of socioeconomic factors on the inequalities in life expectancy and mortality among older groups (≥65 or ≥85 years) [9-13]. On the contrary, studies among younger groups keep multiplying, the majority of them reporting that the most deprived places have lower life expectancies.

Some studies suggest the impact of socioeconomic deprivation later in life is smaller than among younger ages [14, 15]. Contradicting this way of thinking, Huisman found that in certain countries socioeconomic inequalities in old-age mortality can be as large as those in middle life [13]. Engelman et al found compelling evidence that older populations are quite unequal [16]. They observed that, although overall mortality variation decreased, survivors to older ages have become increasingly heterogeneous in their mortality risks, suggesting that mortality inequalities are shifting in age as survival in early life improves [16]. Furthermore, even if relative differences between socioeconomic groups are smaller among elderly, in absolute terms, subtle variations represent a large number of potentially preventable deaths [13]. It is then crucial to identify which (and why) populations survive to more advanced ages and which fall short this mark.

In a previous study, we have identified several-fold differences in old-age survival across more than four thousand European small areas [17]. We believe that a large share of this variation can be attributed to the socioeconomic characteristics of the places. We also suppose there are cross-national and gender differences in the association between survival and socioeconomic deprivation. A dozen of studies have compared the socioeconomic gradient in health across different welfare states and identified noteworthy differences, with the more generous welfare regimes having generally narrower socioeconomic inequalities [18-20]. However, these findings are inconsistent and none of these studies has looked at old-age survival [21]. There is also evidence that the socioeconomic gradient in health might be stronger among men than in women [22-25], yet not all studies support this conclusion [26, 27], and we do not know the pattern later in life.

The purpose of this study was then to determine whether spatial inequalities in old-age survival in Europe are associated with area socioeconomic deprivation. Our research was oriented by the following research questions: 1) is there any association between old-age survival and socioeconomic deprivation and what is the magnitude of those associations, 2) do they vary by country and gender, and 3) how much could old-age survival be improved by eliminating and/or reducing socioeconomic differences between areas? To answer these questions we derived a measure of old-age survival for 1911 small areas of five European countries based on census data. And, to guarantee cross-national comparability, we used a recently developed multivariate measure of socioeconomic deprivation for European countries.

Our study included five European countries and the 1911 into which they are divided: Portugal (308 'municípios'), Spain (337 'comarcas'), France (329 'arrondissements'), England (318 'local authorities') and Italy (619 'distrettos sanitarios'). The average total population per area ranged from 32,246 in Portugal to 177,853 in France. Minimum population per area was 430 in Portugal and the maximum 4,785,999 in Spain. Despite not covering the entire Europe, they represent two distinct geographical regions – Southern and Western Europe [28] – and different welfare regimes [29] – England, generally labeled as Liberal; Spain, Portugal and Italy, positioned in the Southern Europe regime; and France classified as Conservative/Corporatist/Bismarckian.

Outcome: Old age survival

Life expectancy and mortality data in old ages was not disclosed for small areas and, even if available, the calculus of life expectancy in late life for small geographical units comes with well documented problems [30, 31]. Consequently, we had to derive a measure of old-age survival ($r_i = \frac{y_i}{n_i}$) that expresses the probability of the people aged 75-84 years survive for an additional ten years, i.e., surpass the average life expectancy. Where r_i is a ten-year survival rate, i = 1,...,1911, denotes area, the variable y_i represents the population aged 85-94 years old in 2011 and n_i the population aged 75-84 years old ten years before, in 2001 [17]. To calculate this rate we obtained population counts from the Statistic Offices of each country, by 5-year age groups (75-79, 80-84, 85-89, and 90-94), gender, census year (2001 and 2011), and by the smallest geographical area available.

Covariate: Socioeconomic deprivation

European Deprivation Index (EDI) was used to classify small areas according to their level of socioeconomic deprivation (Figure 1). The EDI is a transnational multivariate index developed for five European countries, France England, Italy, Spain, and Portugal [32].The construction of EDI took three steps and has included both individual and aggregated data: 1) construction of an individual indicator of deprivation, based on EU-SILC (EU-Statistics on Income and Living Conditions); 2) identification of variables available both at individual level (EU-SILC) and at aggregate level (population census); and 3) identify the variables selected at step 2 that were associated with individual deprivation, which were then included in the formula of the EDI. The variables that compose the individual and ecological deprivation indicators differed by country, but were comparable, as were chosen under the same methodological and theoretical framework. The final index resulted from the weighted sum of these variables, being the weights the regression coefficients of the association between individual deprivation and census variables. Included variables and weighting are shown in Table 1. The index was standardized and classified into ten classes (C_1 – least to C_{10} – most deprived). Cut-offs, theoretical deciles, were defined based on standard deviations to the overall mean, and they were then customized so that the classes included a balanced number of areas (cut-offs=-1.28,-0.84, -0.52, -0.25, 0, 0.25, 0.52, 0.84, and 1.28) [33].

Statistical model

To take into account the spatial autocorrelation and large variance of small areas, we used Hierarchical Bayesian spatial models. And to account for the fact that the effect of each deprivation class depends on the effect of the previous (ordered categorical covariate), and to allow for flexible slopes in the risk curve, flexible regression models were employed [34].

We assumed that the response variable, number of survivors (Y_i) in each ith area follows a Binomial distribution where p_i is an unknown survival rate and n_i the population aged 75-84 years old ten years before (equation 1).

$$Y_i \sim Bin\ (n_i, p_i) \quad \text{(equation 1)}$$

$$logit(p_i) = \eta_i = \beta x_i + f(x_i) + s_i \quad \text{(equation 2.1)}$$

$$s_i = \tau(\sqrt{\varphi} * u_i + \sqrt{1-\varphi} * v_i) \quad \text{(equation 2.2)}$$

where the mean is linked to a structured additive predictor η_i through a link-function logit. Here βx_i represent the linear effect of covariates gender and country; $f(x_i)$ represent the non-linear/smooth effect of the covariate socioeconomic deprivation accounting for an interaction between gender and country, so that there is one non-linear smooth effect for each gender and country combination (equation 2.1). More specifically, $f(x_i)=e_{jkl}$, where $j=1,2$ denotes gender, k= country and l = 1…10 denotes the deprivation classes. The deprivation classes form the knots of a first order random walk prior over the deprivation classes, that is, a Normal distribution, whose mean is

Table 1. Formula for the calculus of the ecological deprivation index (EDI) score in England, France, Italy, Portugal and Spain – selected variables and weighting.

Country	Score calculus
France	EDI=0.21*Overcrowding +0.71*No bath or shower +1.02*Non-owner +0.71*No car +1.00*Single-parent household +0.97*Household with ≥6 persons +1.17*No high education level +0.57*Low-income occupations +0.94*Unemployed +0.41*Foreign nationality
Italy	EDI =0.83*Overcrowding +2.08* No bath or shower +0.56* No indoor flushing +1.07*Non-owner +0.15* No married +0.33* Women aged ≥65 yrs +1.07* No high education level +0.19* Low-income occupations +1.18* Unemployed
Portugal	EDI =0.40*Overcrowding +0.06* No bath or shower +1.46* No indoor flushing +1.19* Non-owner +0.25* Women aged ≥65 yrs +1.29* No high education level +0.01* Low-income occupations +0.37* Unemployed
Spain	EDI =0.49*Crime/vandalism +0.99*Overcrowding +1.33* No bath or shower +0.73* Non-owner +1.74* No car +0.37* No married +1.30* No high education level +0.95* No employer with employees +0.62* Low-income occupations
England	EDI =0.95*Overcrowding +0.85*No detached house +1.46* Non-owner +0.83* No car +1.35* Single-parent household +0.45* No married +0.98* Permanently disabled or/and unfit to work +0.31* No high education level +0.39* Low-income occupations

an average of e_{jkv} where v denotes the deprivation classes before and after class l.

The s_i is the spatial effect, a reparametrization of the original BYM model [35], considered as a weighted sum of a structured scaled spatial effect u_i and an unstructured effect v_i (equation 2.2), φ measures the amount of s_i attributed to the structured part and τ is the precision and relates to the variance associated to the spatial effect.

Three different measures of goodness of fit were used (Deviance Information Criteria, Watanabe-Akaike Information Criterion and Conditional Predictive Ordinate) to compare models and identify the best one (equation 2.1), that with the lowest value.

Socioeconomic deprivation relative risks (RR) and 95% credible intervals (95% CrI) were derived from their posterior means and quantiles. Due to the presence of interaction effects, RRs will be presented by country and gender. The RR expresses the 'risk' of survival in an area with a certain deprivation level compared to the average survival of the country and gender. An RR would be considered significantly higher or lower if its 95% CrI does not include the one. We will also present summary statistics of the posterior estimates of old-age survival rates for each gender, country and deprivation class.

Posterior distributions were obtained using the Integrated Nested Laplace Approximation (INLA), implemented in the R "INLA" library [36].

Population attributable risk proportion and preventable proportion

We calculated the population attributable risk proportion (PAR) by adapting the formulas purposed by Rockhill [37] and Koopman [38]. Our formula (equation 3) allowed to estimate what would be the decrease in old-age deaths in the absence of socioeconomic deprivation, i.e., if the 'risk' of survival in the 1911 areas was equal to the risk of the

$$PAR = \frac{\sum_{i=1}^{n} P_i\ (RR_1 - RR_i)}{1+\sum_{i=1}^{n} P_i\ (RR_1 - RR_i)} \quad \text{(equation 3)}$$

where RR_i refers to the RR associated to each of the i deprivation class C_i and P_i the corresponding proportion of the total population aged 75-84 years old in 2001.

$$PP = \frac{\sum_{i=2}^{n} P_i\ (RR_{i-1} - RR_i)}{1+\sum_{i=1}^{n} P_i\ (RR_1 - RR_i)} \quad \text{(equation 4)}$$

Because the elimination of the socioeconomic inequalities might not be (easily) achieved, a more realistic measure of was also used. The preventable proportion (PP) estimates what would be the decrease in old-age mortality if the areas moved a class upwards in the socioeconomic spectrum (C_2 to C_1, C_3 to C_2 …) (equation 4).

Both proportions (PAR and PP) were used to compute the absolute and relative number of "additional" survivors after improvement in socioeconomic deprivation by mul-

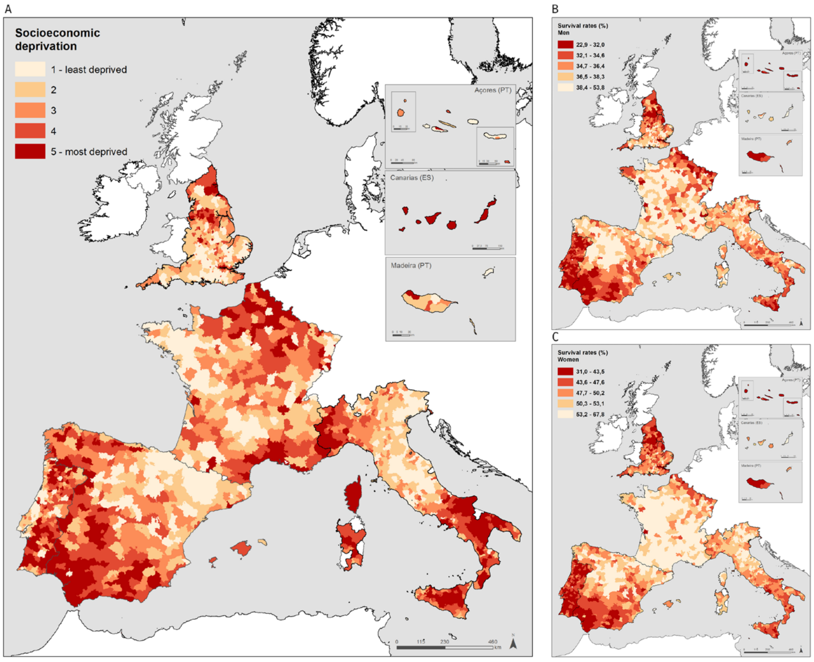

Fig. 1 Spatial distribution of the European deprivation index (A) and of the ten-year old-age survival rates across European small areas (B-men; C-women). Classes defined based on quintiles.

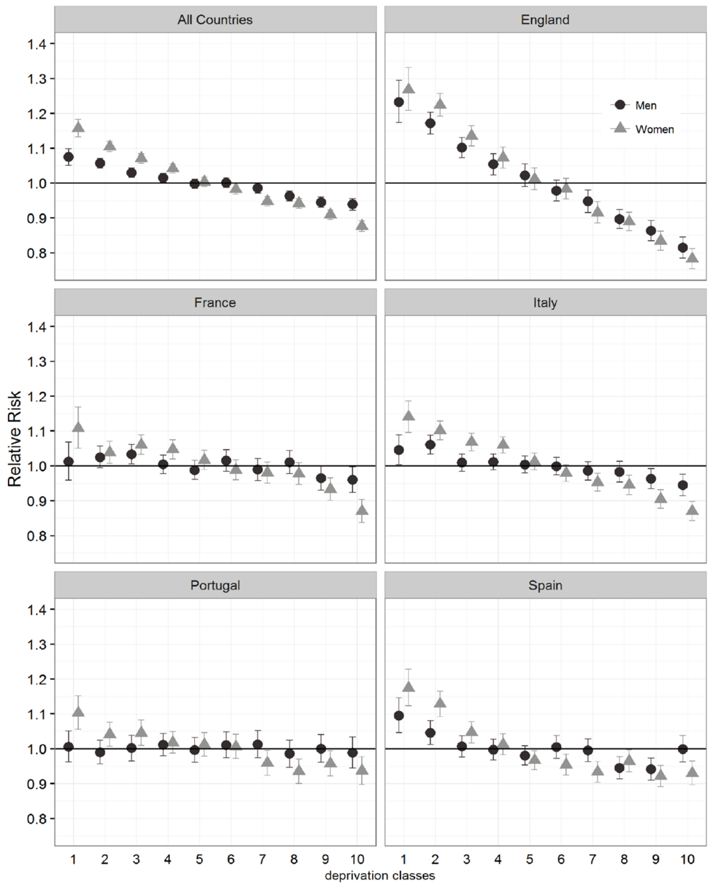

Fig. 2 Association between old-age survival and area socioeconomic deprivation according to gender and country. Relative Risks (RR) and 95% Credible Intervals (95%CrI).

Table 2. Posterior means of the old-age survival rates according to socioeconomic deprivation classes, and increase in old-age survival related with improvement in socioeconomic deprivation (men).

	C_1 least deprived	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10} most deprived	Increase in old-age survival % (absolute increase)	
											Based on PAR[a]	Based on PP[b]
All												
Mean	37.4	36.9	36.2	35.9	35.4	35.5	34.8	33.9	33.0	32.4		
No. areas	86	268	265	269	220	180	140	149	139	195		
Population (%)	3.2	13.0	14.5	13.7	12.6	8.6	6.8	8.4	8.4	10.8	14.1 (236,181)	3.2 (53,527)
England												
Mean	40.3	37.8	36.0	34.8	34.0	33.4	32.5	31.1	29.9	28.0		
No. areas	10	58	53	36	24	29	17	31	24	36		
Population (%)	1.9	12.5	17.1	11.4	7.2	8.3	4.9	12.5	10.1	14.1	38.7 (142,449)	9.4 (34,559)
France												
Mean	38.9	37.7	38.3	37.9	37.1	38.4	36.4	38.1	35.4	34.8		
No. areas	6	40	56	56	43	32	27	23	17	29		
Population (%)	1.1	9.6	13.4	15.1	11.5	9.7	6.4	10.8	6.1	16.4	2.0 (8569)	0.7 (2876)
Italy												
Mean	37.5	37.4	36.1	36.3	36.2	35.7	35.3	35.6	34.2	33.3		
No. areas	21	92	83	99	70	61	48	38	42	65		
Population (%)	3.8	17.8	14.6	15.8	11.3	10.1	8.8	4.9	5.5	7.4	6.4 (30,459)	1.7 (7967)
Portugal												
Mean	32.9	31.9	32.3	32.1	31.7	32.2	31.8	30.6	31.9	30.7		
No. areas	23	39	30	43	37	31	22	28	24	31		
Population (%)	13.3	17.5	8.9	21.8	7.7	7.7	6.9	4.9	5.8	5.7	0.8 (551)	0.1 (83)
Spain												
Mean	39.7	38.6	37.0	37.5	36.5	37.6	36.3	34.6	33.4	34.7		
No. areas	26	39	43	35	46	27	26	29	32	34		

[a]In the absence of socioeconomic differences between areas. [b]If the areas moved a class upwards in the socioeconomic spectrum.

Table 3. Posterior means of the old-age survival rates according to socioeconomic deprivation classes, and increase in old-age survival related with improvement in socioeconomic deprivation (women).

	C_1 least deprived	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10} most deprived	Increase in old-age survival % (absolute increase)	
											Based on PAR[a]	Based on PP[b]
All												
Mean	52.2	51.1	50.7	50.2	49.0	48.2	47.2	46.2	44.8	43.4		
No. areas	86	268	265	269	220	180	140	149	139	195		
Population (%)	3.1	12.8	14.3	13.5	12.7	8.6	6.8	8.3	8.6	11.2	14.6 (525,339)	3.6 (128,234)
England												
Mean	52.2	50.0	47.7	46.1	44.5	44.2	42.2	41.3	39.4	37.0		
No. areas	10	58	53	36	24	29	17	31	24	36		
Population (%)	1.8	12.1	16.8	11.2	7.1	8.4	5.0	12.8	10.3	14.5	27.5 (201,466)	6.5 (48,001)
France												
Mean	57.4	54.4	55.3	55.2	54.1	54.1	52.4	53.6	50.7	48.4		
No. areas	6	40	56	56	43	32	27	23	17	29		
Population (%)	1.1	9.3	13.1	14.4	11.1	9.3	6.3	10.9	6.4	18.2	9.3 (88,986)	2.3 (21,702)
Italy												
Mean	53.6	52.2	51.2	51.2	50.1	48.9	48.2	48.4	46.2	44.7		
No. areas	21	92	83	99	70	61	48	38	42	65		
Population (%)	3.8	18.0	14.8	15.9	11.5	10.2	8.7	4.7	5.3	7.1	10.7 (112,095)	2.9 (30,085)
Portugal												
Mean	46.7	44.6	44.8	43.8	43.5	43.6	42.0	40.6	42.3	40.7		
No. areas	23	39	30	43	37	31	22	28	24	31		
Population (%)	13.6	17.7	8.6	23.6	7.2	7.3	7.2	4.5	5.4	4.9	9,7 (14,248)	2.7 (4010)
Spain												
Mean	54.8	53.7	51.2	51.2	49.3	49.5	47.9	48.1	45.8	45.8		
No. areas	26	39	43	35	46	27	26	29	32	34		
Population (%)	3.8	9.2	13.4	9.4	24.7	5.9	6.5	6.0	15.0	6.2	15.3 (108,544)	3.4 (24,436)

[a]In the absence of socioeconomic differences between areas. [b]If the areas moved a class upwards in the socioeconomic spectrum.

tiplying them by the number of people aged 75-84 who reached 85-94 years old in each country.

Results

On average, the proportion of 75-84 years old population that reached 85-94 was 35.3% (range: 22.9-53.7) among men and 48.5% (31.0-67.8) among women. These figures hide important spatial inequalities, clearly depicted in the maps from Figure 1 (more than a 2-fold difference between areas). The lowest old-age survival rates were observed in Portugal (31.8% and 43.3% for men and women, respectively), followed by England (33.9; 44.8), Italy (35.8; 49.6), Spain (36.6; 49.8), and France (37.4; 53.7).

Tables 2 and 3 depict the average survival rates of each country and gender according to the socioeconomic deprivation classes. Generally, old-age survival decreased as deprivation level increased. From the least to the most deprived areas survival rates experienced a decline of 12% in men and 14% in women. However, the jumps in survival rates between classes of deprivation seemed to be larger in certain countries than in others.

Figure 2 shows the association between the area deprivation and survival rates for each country and gender. The inclusion of the socioeconomic deprivation as covariate reduced the variance of the spatial term (s_i) by 30.8%, meaning that deprivation explains a substantial part of spatial inequalities in old-age survival. Overall there was a significant, and somehow linear, association between socioeconomic deprivation and old-age survival in both genders (Men in least deprived areas RR_1=1.075 (1.052-1.099); Women, RR_1=1.157 (1.132-1.183)). But, important interactions were observed. England was the country where the effect of socioeconomic deprivation was the strongest – the most advantaged areas had about 20% higher survival rates than the most deprived. There, the association followed a clear dose response relationship, with 'chance' of survival increasing as deprivation level decreases (Men RR_1=1.232 (1.174-1.295); Women RR_1=1.268 (1.209-1.331)).

Despite less sharp, the evidence of a dose response relationship was found in Spain and Italy too, where the most advantaged areas registered consistently higher survival rates as compared to the most disadvantaged (RR_1: Italian men, 1.045 (1.003-1.089); Italian women, 1.140 (1.096-1.187); Spanish men, 1.094 (1.046-1.146); Spanish women,1.174 (1.023-1.228)).

Despite a much more subtle pattern – most RRs were in the borderline of the statistical significance – in Portugal and France, women survival rates were significantly higher in the most advantaged end (RR_1: Portugal=1.103 (1.056-1.151); France=1.108 (1.051-1.169)). However, male survival in France, and especially in Portugal, did not seem much related to old-age survival, although there is a tendency (also observable in Table 1) towards decreasing survival rates with deprivation.

By eliminating socioeconomic differences between areas (all areas having the survival levels of the most affluent) we would be able to increase the number of old-age survivors in men by 14.1% and by 14.6% in women, i. e., almost 800,000 fewer deaths within a 10 year period (Tables 2-3). Larger gains would be expected in England (+38.7% in men; +27.5% in women), followed by Spain (+15.8; +15.3) and Italy (+6.4; +10.7). In Portugal and France improvements would be almost irrelevant in men, but still notable among women (9.7% and 9.3%, respectively).

Overall, even if each area moves only a class upward in the socioeconomic spectrum old-age survival could improve by 3.2% and 3.6% in men and women, respectively, that is, roughly 180,000 fewer deaths within a 10 year period in the five countries together.

Discussion

Our study reports that socioeconomic deprivation significantly impacts survival after 75 years of age in five European countries. England was by far the country where the association between socioeconomic deprivation and old-age survival was stronger, with a clear linear effect of decreasing survival as deprivation levels increase. In Italy and Spain a similar, but less steep gradient, was observed, whereas in Portugal and France the trend was only observable in women. Among males from these two countries, we found no evidence that socioeconomic deprivation influences old-age survival. We projected that the elimination of socioeconomic differences between areas would lead to an increase in old-age survival of about 14% and, even a slight reduction on socioeconomic differences, would mean a 3% higher survival in Europe.

Much has already been published on the area-level effect of socioeconomic deprivation on life expectancy at birth and overall mortality [39, 25, 24, 40, 23, 22, 2]. In our study we found that this effect exists later in life too. The probability of people aged 75-84 years reaching more advanced ages was significantly higher in the most affluent areas (15-20% higher) compared to the most disadvantaged. Literature in this topic is sparse, and most studies are between-country comparisons. But, even at this level, they consistently show socioeconomic deprivation matters. A Europe-wide study reported mortality rate ratios (most vs. the least educated) ranging from 1.05 in Norway (men) to 1.39 in Austria (women) [13]; whilst our study design is considerably different, these ratios somehow match ours. Kim [12, 9] constructed a similar indicator (probability of reaching 100 years) and found it was highly correlated with socioeconomic factors, such as health care expenditure, standard of living, and suicide rates (lack of social support). Looking at other endpoint (healthy life expectancy at old ages, HLE), three studies found that material deprivation (particularly healthcare expenditure) explained cross-national HLE inequalities across Europe [10, 11, 41]. The influence of socioeconomic deprivation later in life has been also confirmed by individual level studies, which were recently summarized [8].

In our study we found relevant cross-national differences in the effect of socioeconomic deprivation. Cross-national differences in the impact of socioeconomic factors have been reported by other authors. In a study involving 22 European counties, socioeconomic inequalities in mortality were found to be smaller in some southern European countries and larger in the Eastern and Baltic states [40]. Similarly, researchers of INEQ-CITIES project observed that the effect magnitude of socioeconomic deprivation in all-cause [25], cause-specific [23, 22], and injury related mortality [24] was smaller in the southern than in northern, western and central-eastern European cities. In our study we did not find such clear divide between South and Western Europe. Sure, in England (Western Europe) the effect of socioeconomic deprivation in survival was the strongest, but a rather similar effect was also observable in Italy and Spain.

The welfare regime theory is being increasingly used to understand health inequalities across different nations. Recapping, the welfare regime refers to the state's function in providing services, such as education and social protection. Its role in influencing population health is still under intense debate [21], but the most generous welfare regimes – Scandinavian (e.g. Sweden), Conservative (e.g. France) and, at lesser extent, Southern European (e.g. Portugal, Italy, Spain) – are supposed to 'protect' citizens against the detrimental effects of deprivation better than liberal regimes (e.g. United Kingdom) . The welfare regime theory might then explain the substantial effect of socioeconomic factors in England and their relative mildness in France and Portugal. The type of healthcare system might also contribute to such cross-national differentials in the effect of deprivation; a strong healthcare system that guarantees universal and free population coverage [42] and emphasize primary care [43] might help to ameliorate the effects of socioeconomic deprivation. The countries we evaluated have universal (England, Portugal, Italy) or nearly universal healthcare systems (France, Spain) [44], and have strong (Portugal, England, Spain) or medium primary care systems (Italy, France) [45]. But, we observed that the effect of socioeconomic deprivation was particularly prominent in England, known by its primary care centered health system and for being one of the world's largest publicly funded health services. This 'British paradox' has been discussed by several authors [46].

The social distribution of risk factors might also help to interpreted cross-national differences. Southern European countries have a more egalitarian distribution of health-related behaviors such as tobacco consumption [40, 47] than Northern countries; that might explain the lesser impact of socioeconomic deprivation in Portugal among men, and the stronger effect in England. But, again, it does not explain the position of Spain and Italy, where health-related behaviors are also equally distributed, neither the reduced impact of deprivation in France (as mature in epidemiology transition as England). Regarding obesity, the social stratification of this condition is inverse – larger in Southern than in Western Europe countries such as England [48, 40]. However, this pattern does not contribute much to the interpretation of our results.

Finally, the different degree of socio-spatial segregation could also contribute to the cross-country differences in the effect of deprivation. Socio-spatial segregation refers to the extent to which similar societal groups (based on income, ethnicity) reside close to each other. The patterns of spatial segregation usually have deep and old origins. Focused on the UK, several studies have been highlighting the strong socio-spatial segregation of the British population, with the most deprived working classes living at north and the more affluent classes in the south and London area [49]. However, the socio-spatial segregation patterns in France, Italy, Portugal or Spain are not well-documented.

We did not observe substantial gender differences in the effect of socioeconomic deprivation on survival; specifically we did not find them to be stronger among men, contrasting with articles that report men are more susceptible to the socioeconomic circumstances [22-25]. Yet other studies showed that these gender differences do not exist or can be more evident among women [26, 27, 50]. Indeed, we observed the effect of deprivation on old-age survival were slightly larger among women and, in Portugal and France practically absent in men. It is actually plausible that inequalities among women become wider later in life. Due to a delayed health selection the pool of women that reaches advanced ages it is expected to be more diverse in terms of socioeconomic characteristics.

Some limitations of the study must be discussed. Although we tried to use areas as comparable as possible, in some countries the areas were larger than in others. It is usually recommended to use the smallest units possible – large areas level off socioeconomic and health indicators, obscuring important relationships and inequalities. Consequently, we might have underestimated the true dimension of the effect of deprivation on old-age survival and eventually fail to detect significant associations. Our study is also grounded on the assumption that people have lived in the same area during 10 years; migration of population aged 75 years or more has been shown to be infrequent [51] but it remains a possibility. And, there is also evidence the presence of residential mobility, at most, would cause an underestimation of the spatial inequalities and socioeconomic effects [52].

Our study has numerous strengths as well. We were able to collect homogeneous and internationally comparable data at small area level for five countries and derived a measure of old-age survival for small areas that is as a valuable alternative to life expectancy in older ages. Building internationally comparable datasets to monitor health inequalities is a top priority. Moreover, we have employed a transnational multivariate index of socioeconomic deprivation to quantify the association between deprivation and old-age survival. This was not done before at least with such Europe-wide extent (INEQ-Cities project follow similar approach but only covered metropolitan areas [22-25]). The cross-national studies on the impact of socioeconomic factors have been using single (not composite) indicators of socioeconomic deprivation (education, income, or occupation), which do not fully capture the multifactorial nature and the context specificity of deprivation.

Socioeconomic deprivation seems to shape the survival probability of the European oldest-old. Policy makers should then keep focusing on poverty and deprivation as a weapon to reduce differences in mortality and life expectancy, and these policies should aim the oldest-old as well. They also need to guarantee that interventions do not reinforce these inequalities.

With our methodology, the success and failure of such policies can be easily monitored through time and space. But, preferably, the European community should make an effort to gather health and socioeconomic indicators at small area level to facilitate the study and monitoring of the inequalities in health across the entire Europe. It is crucial to definitely understand why socioeconomic gradients in survival (and health) vary so much across Europe – is welfare provision acting as a buffer against the detrimental effects of deprivation, or are there other forces (informal support networks, cultural aspects) performing in parallel?

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Authors' contributions

AIR designed the study, performed the statistical analysis and drafted the manuscript. EK performed the statistical analysis and helped to draft the manuscript. GL and CP coordinated the development of the European Deprivation Index, helped draft the manuscript and contributed to the interpretation of results. MSC and MFP helped designed the study, supervised the research, contributed to the interpretation of results and helped to draft the manuscript. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of Interest
The authors declare that they have no conflict of interest.

Ethical Approval
For this type of study formal consent is not required. This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent
Informed consent is not needed for this paper since we had no information on individual human subjects.

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5.4. The influence of socioeconomic deprivation, access to healthcare and physical environment on old-age survival in Portugal (paper IV)

The influence of socioeconomic deprivation, access to healthcare and physical environment on old-age survival in Portugal.

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Abstract
Background: Spatial inequalities in old-age survival exist in Portugal and might be related with factors pertaining to distinct domains, socioeconomic, physical environmental and healthcare-related. In this study we aimed to evaluate the contribution of these factors on the old-age survival in the 278 Continental Portuguese municipalities.
Methods: We derived a surrogate measure of life expectancy, a ten-year survival rate that expresses the proportion of population aged 75-84 years who reached 85-94 years old. As covariates we have used two internationally comparable ecological multivariate indexes – the European deprivation index and the multiple physical environmental deprivation index. A national indicator was developed to evaluate the access to healthcare for older population. Smoothed rates and relative risks (RR) were estimated using Bayesian spatial models.
Results: Socioeconomic deprivation was the most relevant factor influencing old-age survival in Portugal (Women: least deprived areas RR_1=1.132 (1.064-1.207); Men RR_1=1.044 (1.001-1.094)) and explained a sizable amount of the spatial variance in survival, especially among women. Access to healthcare was slightly associated with old-age survival but results did not reached statistical significance after adjustment for socioeconomic circumstances (Women: higher access to healthcare RR_1=1.020 (0.973-1.072); Men RR_1=1.021 (0.989-1.060)). Physical environmental deprivation was unrelated with old-age survival.
Conclusion: This geographical cleavage was partially explained by two of the three factors we incorporated in the analysis. Socioeconomic deprivation was the most important determinant of old-age survival, followed by access to healthcare. Physical environmental deprivation did not explain the geographical pattern of old-age survival.

What is already known on this subject?
- At the current stage of the epidemiological transition, old-age survival is a good summary indicator of population health.
- In Portugal there are clear spatial inequalities in the distribution of the chances of survival after 75-84 years of age.
- These differences might result from diverse multidimensional factors that interact with each other.

What this study adds?
- This is the first study addressing the impact of socioeconomic, physical environmental and healthcare-related factors on old-age survival.
- These factors were measured using methodologically sound and internationally comparable indexes.
- Spatial inequalities in the distribution of old-age in Portugal were partially explained by these factors.
- Socioeconomic deprivation was by far the most important determinant of old-age survival.

INTRODUCTION

In high income countries, premature mortality has plateaued at very low levels, and, consequently, old-age survival is now the mechanism that regulates life-expectancy.[1] Old-age survival is then a good general indicator of population health and development. Although overall mortality variation decreased, survivors to older ages have become increasingly heterogeneous in their mortality risks, which suggest that mortality inequalities are shifting to older ages as survival in early life improves.[2 ,3]

Spatial inequalities in health, and in particularly in old-age survival, exist in Portugal, and might be related with diverse factors that interact with each other.[4]
Socioeconomic factors must play an important role in explaining these spatial differentials, but diverse studies have shown that in southern Europe the association between health and socioeconomic deprivation tends to be rather modest compared to Western Europe.[5-9]

Other factors might compete with socioeconomic deprivation in explaining these spatial differentials. There is evidence that the characteristics of the physical environment contribute to extend or shorten life expectancy among older adults.[10-12] Among all age groups, the elderly are certainly the most affected by the impact of climate extremes[13 ,14] and air pollution.[15 ,16] Detrimental physical environments are not randomly distributed. Several studies have found that physical and socioeconomic deprivation coincide in space (the so-called environmental injustice)[17], and, consequently, the two should be taken into account when studying health inequalities.[18]

The access to healthcare is a vital aspect, especially at older ages due to the heavy burden of chronic diseases and to higher susceptibility to infections. The likelihood of surviving beyond certain age is certainly affected by use of the healthcare resources.[19] The importance of healthcare is patent in several European studies, which revealed that the fast increase in old-age survival of the past decades can be mostly attributed to improvements in healthcare.[19-21]

These intricate relations between socioeconomic, physical and healthcare factors can only be understood with the use of indicators that grasp the multifactorial nature of these influences. Multivariate ecological indexes of socioeconomic deprivation are becoming common place[22 ,23] as epidemiology research shifts from its traditional biomedical focus to an eco-social approach. But, multivariate indicators about the physical environment and access to healthcare are still uncommon.

In this study we aimed to evaluate the role of each of these influences (socioeconomic, physical environmental and healthcare factors) on old-age survival in Portugal. We derived a measure of old-age survival for the 278 small areas of Portugal based on census data. And, as covariates, we used evidence-based ecological indexes.

METHODS

Study area

The study was conducted in Continental Portugal, using municipalities as units of analysis. Municipalities are commonly the smallest unit for health data dissemination and, apart from the large urban areas, they tend to be homogeneous in terms of social and economic profile. Two hundred and seventy eight municipalities exist in Continental Portugal with an average population of 36,143 inhabitants (range: 1834-547,733) in 2011.

Old age survival

Because life expectancy and mortality data in old ages was not disclosed for small areas, we had to derive a measure of old-age survival ($r_i = \frac{y_i}{n_i}$) that expresses the probability of the people aged 75-84 years survive for an additional ten years, i.e., surpass the average life expectancy.[4] Where r_i is a ten-year survival rate, i =1,...,1911, denote area, the variable y_i represents the population aged 85-94 years old in 2011 and n_i the population aged 75-84 years old ten years before, in 2001. Population census data of 2001 and 2011 was provided by Statistics Portugal (INE, Instituto Nacional de Estatística).

Covariates

Socioeconomic deprivation

The European Deprivation Index (EDI) was used to classify small areas according to their level of socioeconomic deprivation (Figure 1). The EDI is a transnational multivariate index developed for five countries: France, England, Italy, Spain, and Portugal.[23] The construction of EDI took three steps and included both individual and aggregated data: 1) construction of an individual indicator of deprivation, based on EU-SILC (EU-Statistics on Income and Living Conditions); 2) identification of variables available both at individual level (EU-SILC) and at aggregate level (2001 national population census); and 3) identification of the variables selected at 2) that were associated with the individual deprivation, which were then included in the formula of the EDI. The final index resulted from the weighted sum of these variables, being the weights the regression coefficients of the association between individual deprivation and census variables. More details are provided as supplementary material (supplementary material 1). The index was standardized and classified into ten classes (C_1 – least to C_{10} – most deprived) based on standard deviations to the overall mean, customized so that classes included a balanced number of areas (cut-offs=-1.28,-0.84, -0.52, -0.25, 0, 0.25, 0.52, 0.84, and 1.28).

Access to healthcare

Because no standard indicator existed we had to derivate an indicator of access to healthcare for older population (Figure 1). We started by retrieving all datasets on healthcare availability and accessibility (the two domains of healthcare access for which data was available). Variables and indicators were obtained at municipality level, for the year 2001 (whenever possible) and for Continental Portugal, from two data sources: Hospitals and Primary Care Centers Surveys from Statistics Portugal,[24 ,25] and Social Map from the Ministry of Solidarity, Employment and Social Security.[26] From 49 datasets, those with too many missing/censored and zero values were discharged (n=16 datasets selected). Then we calculated rates to express the population exposure to those variables (n=16 variables defined). Variables were then characterized and transformed to become more normally distributed. Subsequently, bivariate correlations were computed to identify variables excessively correlated, which were discharged (n=10 variables selected). Finally, principal component analysis was run to derivate a summary measure expressing access to healthcare in each municipality. The three principal components that explained 72% of the variability in the latent variable access to healthcare were:

1) Availability of long-term care and social support facilities – capacity of the daycare centers; capacity of the nursing homes; capacity of the home care;
2) Availability and geographical accessibility to healthcare facilities - population weighted mean distance to public hospitals; primary care centers and extensions; pharmacies and mobile pharmacy posts;
3) Availability of health professionals – medical doctors by place of residence; nurses by place of work; dentists by place of residence; and pharmacists by place of work.

For each municipality, i, each component score was multiplied by the proportion of variation explained (equation 1).

$$AHI\ score_i = 0.25340 * 1st\ component_i + 0.23857 * 2nd\ Component_i + 0.22924 * 3rd\ component_i \qquad \text{(equation 1)}$$

Similarly to socioeconomic deprivation, after standardization, the index was categorized into 10 classes.

Physical environmental deprivation

The measure of multiple physical environmental deprivation (PT-MEDIx) (Figure 1) was builtat municipality level in four stages [27]: (i) identification of health-relevant environmental factors through literature review; (ii) acquisition of datasets about selected environmental factors and calculation of municipality-level exposure measures; (iii) testing associations between selected factors and mortality; and (iv) construction of a summary measure and assessing its association with mortality. The PT-MEDIx covered five dimensions of the physical environment: air pollution (particulate matter, nitrogen dioxide, carbon monoxide); climate (temperature); drinking water quality (trihalomethanes and nitrates); greenspace availability; and industry proximity. Municipalities in the highest quintile of exposure received a score of +1 for harmful factors and -1 for beneficial factors. The PT-MEDIx of each municipality resulted from the sum of these scores and ranged from -1 (least environmental deprivation) to +4 (most).

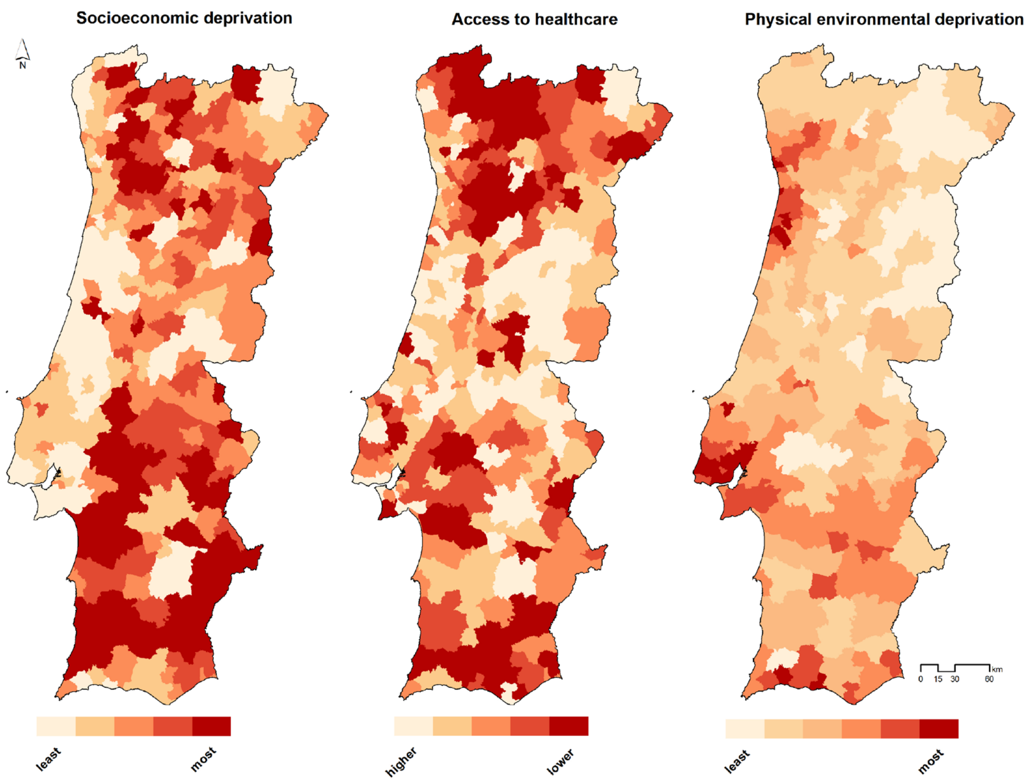

Figure 1. Spatial distribution of socioeconomic deprivation, access to healthcare, and physical environmental deprivation in Continental Portugal.

Statistical model

To take into account the spatial autocorrelation and the large variance of small areas, we used Bayesian spatial models. And giving the fact that the effect of each deprivation class depends on the effect of the previous (ordered categories), and to allow for flexible slopes in the risk curve, flexible regression models were employed.[28]

We assumed that the response variable, number of survivors (Y_i) in each ith area follows a Binomial distribution where p is an unknown survival rate and n the population aged 75-84 years old ten years before (equation 2).

$$Y_i \sim Bin\ (n, p) \qquad \text{(equation 2)}$$

$$logit(p) = \eta_i = f(x_i) + s_i \qquad \text{(equation 3.1)}$$

$$s_i = \tau(\sqrt{\varphi} * u_i + \sqrt{1-\varphi} * v_i) \qquad \text{(equation 3.2)}$$

The mean is linked to a structured additive predictor η_i through a link-function logit. Here $f(x_i)$ represent the non-linear/smooth effect of the covariates (equation 3.1). More specifically, $f(x_i) = e_l$, where l denotes the classes of socioeconomic deprivation $(l = 1, \ldots 10)$ physical environmental deprivation $(l = 1, \ldots 6)$, and access to healthcare $(l = 1, \ldots 10)$, which defined the knots of a first order random walk spline.

The s_i is the spatial effect, a reparametrization of the original BYM model,[29] considered as a weighted sum of a structured scaled spatial effect u_i and an unstructured effect v_i (equation 3.2). The φ measures the amount of s_i attributed to the structured part; τ is the precision (inverse of the variance) and expresses the amount of variance associated to the spatial effect.

Separate models where run for each gender due to the presence of significant interactions and disparate probabilities of survival. Model from equation 3.1 was our final model, but we have started with a null model, where we included only the spatial effect s_i, and then each covariate was successively introduced. Additionally, univariable models were run in which, besides the spatial effect, a single covariate was included. The presence of interactions was also investigated.

Three different measures of goodness of fit were used (Deviance Information Criteria, Watanabe-Akaike Information Criterion, and Conditional Predictive Ordinate) to compare models. The relative reduction in the variance of spatial effect (τ) was also evaluated to ascertain in what extent covariates contributed to explain the spatial variation in old-age survival.

Relative risk (RR) estimates and 95% credible intervals (95% CrI) were derived from their posterior means and quantiles, and expresses the 'risk' of survival in the areas with a certain level of the covariate as compared to the average survival. A RR was considered significantly higher or lower if its 95% CrI did not include the value 1. Posterior distributions were obtained using the Integrated Nested Laplace Approximation (INLA), which was implemented in the R INLA library.[30]

RESULTS

On average, the old-age survival rates were 32.3% (maximum=39.7; minimum=27.5) among men and 43.7% (67.2; 34.5) among women. The presence of spatial inequalities in the distribution of survival is depicted in Figure 2, showing a nearly two-fold difference between areas.

In Figure 3, the survival rates are represented as a function of each covariate. In general, survival rates decreased with socioeconomic deprivation in both genders. Despite the trend did not look as steepest, survival rates declined as access to healthcare decreased. The association with physical environmental deprivation did not follow the expected pattern – the highest survival rates seemed to occur in the poorest physical environments.

The results obtained with the univariate models confirmed these patterns (results not shown): a negative association with socioeconomic deprivation (stronger among women), a positive association (but weaker) with access to healthcare, and no association with physical environmental deprivation.

The associations (RR and 95%CrI) between old-age survival and the three considered covariates are shown in Table 1 (men) and 2 (women). In the Model 0, the percent variability attributed to the spatial random effect was 51% and 65% in men and women, respectively. We then added one variable at each time to assess its impact on old-age survival.

Among women, as told before, a rather linear association between old-age survival and socioeconomic deprivation was observed. The variance attributed to the spatial effect was reduced by 31.4% after including this variable. The inclusion of the remaining variables did not cause much change in the adjustment parameters nor in the variance explained by the spatial effect. Still, it seems that higher access to healthcare improves survival rates (higher availability and accessibility to healthcare RR_1=1.020 (0.973-1.072)). The association between socioeconomic deprivation and survival was maintained after the inclusion of the remaining covariates (least deprived areas RR_1=1.132 (1.064-1.207)). As observed in Figure 3, environmental deprivation was associated with increased survival, but, as happens with access to healthcare, results were not statistically significant.

Among men we found similar results, although the magnitude of the associations was considerably smaller. Socioeconomic deprivation was significantly associated with survival among men (RR_1=1.044 (1.001-1.094)), but the reduction of spatial variance caused by the introduction of that variable was relatively small (13.1%). As observed among women, access to healthcare was also somehow associated to survival (higher access to healthcare RR_1=1.021 (0.989-1.060)) and the effect of environmental deprivation went in the opposite direction. Regardless of gender, no significant interaction effects were observed.

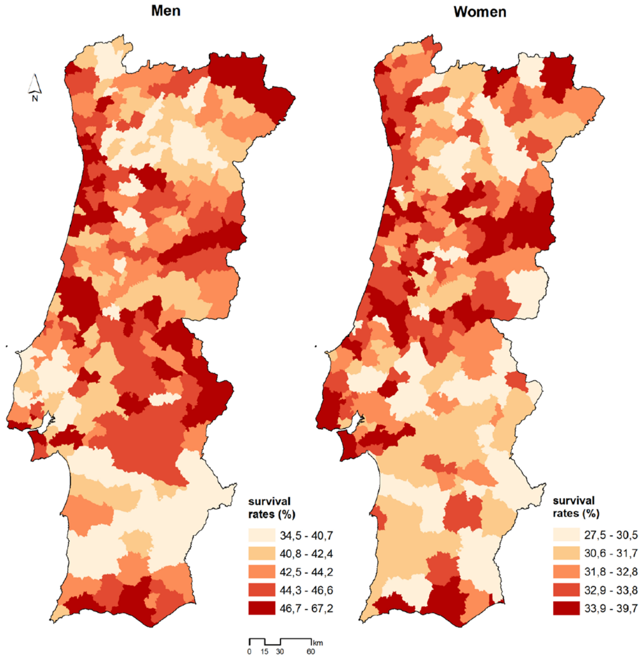

Figure 2. Spatial distribution of the posterior old-age survival rates for men (left) and women (right).

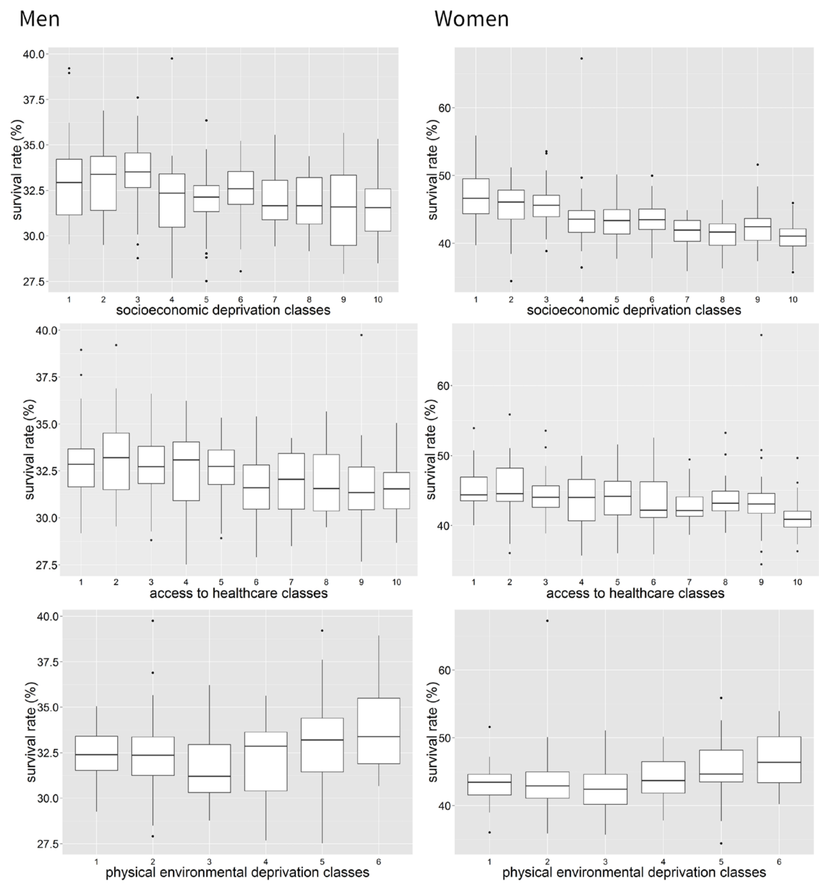

Figure 3. Posterior old-age survival rates as a function of socioeconomic deprivation, healthcare availability, and physical environmental deprivation, for men (left) and women (right).

Table 1. Association between old-age survival and socioeconomic deprivation, access to healthcare, and physical environmental deprivation (Men).

	Model 0	Model 1	Model 2	Model 3
	RR (95%CrI)[a] (No covariates, only spatial effect)	RR (95%CrI) (socioeconomic deprivation only)	RR (95%CrI) (plus healthcare)	RR (95%CrI) (plus healthcare and physical environment)
Socioeconomic deprivation				
1 (least deprived)		**1.051 (1.008-1.101)**	**1.043 (1.001-1.092)**	**1.044 (1.001-1.094)**
2		**1.042 (1.008-1.080)**	**1.035 (1.001-1.073)**	**1.035 (1.001-1.073)**
3		**1.040 (1.004-1.086)**	1.034 (0.999-1.079)	1.033 (0.999-1.077)
4		1.004 (0.971-1.035)	1.006 (0.975-1.037)	1.006 (0.976-1.037)
5		0.974 (0.935-1.007)	0.978 (0.939-1.009)	0.977 (0.939-1.008)
6		0.991 (0.959-1.026)	0.991 (0.960-1.023)	0.989 (0.957-1.020)
7		0.991 (0.954-1.031)	0.991 (0.956-1.029)	0.989 (0.954-1.026)
8		0.983 (0.947-1.021)	0.986 (0.952-1.002)	0.987 (0.952-1.022)
9		0.969 (0.931-1.005)	0.973 (0.935-1.008)	0.974 (0.936-1.008)
10 (most deprived)		0.959 (0.915-1.001)	0.967 (0.922-1.008)	0.970 (0.926-1.011)
Access to healthcare				
1 higher			1.020 (0.988-1.061)	1.021 (0.989-1.060)
2			1.025 (0.997-1.062)	1.024 (0.997-1.060)
3			1.016 (0.991-1.049)	1.016 (0.991-1.047)
4			1.005 (0.978-1.038)	1.005 (0.980-1.033)
5			1.003 (0.977-1.033)	1.002 (0.977-1.030)
6			0.986 (0.951-1.010)	0.987 (0.957-1.014)
7			0.989 (0.960-1.013)	0.988 (0.960-1.012)
8			0.987 (0.955-1.015)	0.987 (0.957-1.014)
9			0.983 (0.950-1.011)	0.984 (0.952-1.011)
10 lower			0.987 (0.949-1.022)	0.986 (0.950-1.021)
Physical environment				
-1 least env. deprived				0.995 (0.950-1.039)
0				1.001 (0.972-1.032)
1				0.974 (0.938-1.004)
2				0.991 (0.959-1.019)
3				1.017 (0.985-1.058)
4 most env. deprived				1.023 (0.978-1.082)
DIC[b]	2268.56	2268.58	2269.45	2269.15
WAIC[b]	2260.95	2263.53	2264.69	2263.71
CPO[b]	-1065.36	-1066.65	-1070.99	-1072.39
Reduction of spatial effect[c]	---	13.1	18.7	23.7

[a]Relative Risks, RR, and corresponding 95% Credible Intervals, 95%CrI.
[b]DIC=Deviance Information Criteria; WAIC=Watanabe-Akaike Information Criterion; CPO=Conditional Predictive Ordinate.
[c]Percent reduction in the variance of the spatial effect (structured and unstructured).
In bold, statistically significant results.

Table 2. Association between old-age survival and socioeconomic deprivation, access to healthcare, and physical environmental deprivation (Women).

	Model 0	Model 1	Model 2	Model 3
	RR (95%CrI)[a] (No covariates only spatial effect)	RR (95%CrI) (socioeconomic deprivation only)	RR (95%CrI) (plus healthcare)	RR (95%CrI) (plus healthcare and physical environment)
Socioeconomic deprivation				
1 (least deprived)		**1.146 (1.079-1.222)**	**1.135 (1.068-1.210)**	**1.132 (1.064-1.207)**
2		**1.087 (1.038-1.138)**	**1.080 (1.032-1.131)**	**1.080 (1.032-1.129)**
3		**1.083 (1.031-1.142)**	**1.074 (1.025-1.132)**	**1.072 (1.023-1.128)**
4		1.029 (0.986-1.074)	1.032 (0.990-1.077)	1.032 (0.990-1.077)
5		0.994 (0.951-1.037)	0.994 (0.952-1.035)	0.994 (0.952-1.035)
6		0.986 (0.943-1.033)	0.981 (0.939-1.026)	0.978 (0.937-1.022)
7		**0.937 (0.884-0.986)**	**0.940 (0.889-0.987)**	**0.941 (0.890-0.987)**
8		**0.925 (0.876-0.971)**	**0.931 (0.889-0.976)**	**0.933 (0.886-0.978)**
9		**0.940 (0.894-0.991)**	**0.942 (0.897-0.991)**	**0.943 (0.899-0.991)**
10 (most deprived)		**0.903 (0.850-0.955)**	**0.916 (0.862-0.969)**	**0.920 (0.866-0.973)**
Access to healthcare				
1 higher			1.020 (0.971-1.073)	1.020 (0.973-1.072)
2			1.032 (0.994-1.083)	1.032 (0.994-1.081)
3			1.021 (0.984-1.070)	1.020 (0.984-1.066)
4			0.994 (0.947-1.032)	0.996 (0.950-1.032)
5			1.014 (0.977-1.067)	1.011 (0.975-1.061)
6			0.987 (0.941-1.025)	0.988 (0.944-1.025)
7			0.979 (0.933-1.015)	0.980 (0.935-1.015)
8			1.004 (0.964-1.062)	1.003 (0.964-1.058)
9			0.993 (0.954-1.038)	0.992 (0.954-1.036)
10 lower			0.957 (0.896-1.008)	0.961 (0.901-1.009)
Physical environment				
-1 least env. deprived				0.993 (0.945-1.041)
0				0.987 (0.952-1.019)
1				0.972 (0.928-1.006)
2				1.003 (0.971-1.040)
3				1.020 (0.985-1.067)
4 most env. deprived				1.025 (0.974-1.093)
DIC[b]	2478.84	2481.10	2481.43	2481.53
WAIC[b]	2459.71	2471.92	2473.54	2472.88
CPO[b]	-1261.48	-1252.19	-1255.65	-1257.34
Reduction of spatial effect[c]	---	31.4	33.5	35.6

[a]Relative Risks, RR, and corresponding 95% Credible Intervals, 95%CrI.
[b]DIC=Deviance Information Criteria; WAIC=Watanabe-Akaike Information Criterion; CPO=Conditional Predictive Ordinate.
[c]Percent reduction in the variance of the spatial effect (structured and unstructured).
In bold, statistically significant results.

DISCUSSION

In this study we aimed at investigate the contribution of three important multidimensional determinants on old-age survival in Portuguese municipalities. We found that socioeconomic deprivation was the most relevant factor, explaining a considerable share of the spatial variance in old-age survival, especially among women. Despite the evidence showing that physical environment and healthcare affects elder's health,[10-12 ,19] after accounting for socioeconomic deprivation, those factors did not seem to play a major influence in older people's chances of surviving. Access to healthcare was slightly associated with old-age survival and no relation with physical environmental deprivation was observed.

To date very few studies compared the relative importance of factors pertaining from different domains, social, economic, physical environmental.[31-33] These studies have used indicators (outcomes and covariates) that are not directly comparable to ours, but all established that socioeconomic deprivation had the starkest effect. The prominent role of socioeconomic deprivation in shaping population's health has been matter of discussion for centuries and its influence is still observed in our times. For instance in United Kingdom and United States socioeconomic deprivation seems to explain most of the spatial inequalities in health and life expectancy.[33 ,34] Hood reported the relative contributions of socioeconomic factors, health behaviors, clinical care, and the physical environment to health in the United States were 47%, 34%, 16%, and 3%, respectively.[33] However, in our study the association between old-age survival and socioeconomic deprivation was significant but its contribution in explaining spatial effects was modest, reducing the spatial effect by 31% among women and by just 13% in men. It is plausible that other factors counterbalance the effects of socioeconomic deprivation, such as formal and informal social and economic support networks.

Our study is ecological in nature, and consequently we could not clearly ascertain the mechanism by which socioeconomic aspects affects survival. There are numerous theories trying to conceptualize that. One of the most relevant is the (neo)material model, which states that most deprived people have poorer health due to lack of material conditions at home and in the context of living (work, school, neighborhood, region).[35] Our results do not fully accord to this theory. For instance, and contrasting to other studies,[36] we did not found socioeconomic deprivation to be directly related to physical environmental deprivation (not shown), which we have measured by a combination of different exposures (greenspace availability, air/water pollution, climate). Indeed we observed the exact opposite, affluent areas, had the poorest physical environmental conditions. But, we did find evidence that healthcare is less available in more deprived areas (not shown), suggesting some form of environmental unfairness exists in Portugal, as observed in other national study.[37]

Physical environment did not affect old-age survival in our study. Poor physical environments were concentrated in affluent urbanized areas and the positive influence of having good material resources and facilities (e.g. healthcare, jobs, housing conditions) might conceal the detrimental effects of living in a more hazardous environment. The absence of an association with physical environmental aspects might be also attributed to the mortality patterns among very old populations; among the eldest the top mortality cause is cardiovascular disease (CVD, responsible for over 40% of the deaths after the 85 years old). In a previous work about the development of PT-MEDIX,[27] we did not found a significant association between physical environmental deprivation and CVD, but, on the other hand, we observed a strong dose-response relation with cancer mortality. Therefore, the impact of physical environment might be modest among the older population groups less affected by cancer mortality.

When compared to socioeconomic deprivation, the effect of access to healthcare was considerably lesser. Still, we found evidence that good healthcare provision, in terms of geographic access, coverage of hospital and primary care facilities, and healthcare personal, might contribute to extend life-span. However, controlling for socioeconomic characteristics, access to healthcare lost its importance. Likewise our study, but addressing coronary heart disease specifically, Ferreira-Pinto found that socioeconomic circumstances and health resources (in a lesser degree) were associated with both mortality and admission rates at municipality-level in Portugal.[32] International studies have reached similar conclusions - socioeconomic circumstances (followed by healthcare resources) are the greatest determinants of human longevity.[38 ,39]

The main limitation of this study is related with the use of aggregated data. Scale might have influenced our results. Due to lack of higher resolution data, we conducted this analysis at municipality level. Municipalities in Portugal can have as few as 1830 inhabitants or hold over 500,000 inhabitants. Consequently, we might have failed to detect important associations and inequalities. The Modifiable Areal Unit Problem is another potential source of bias. A different arrangement of the spatial units might have yield different results. Our study was also grounded on the assumption that people have lived in the same area during 10 years; migration of population aged 75 years or more has been shown to be infrequent[40] but it remains a possibility. Finally, we were not able to evaluate the role of other potentially important aspects, like social support or certain features of the built environment (recreation, destinations, food offer), which might account for the remaining spatial effect that our statistical model was not able to explain.

Our study has numerous strengths as well. Firstly, we were able to derive a measure of old-age survival for small areas that can be used as an alternative to life expectancy in older ages. Secondly, very few studies have dealt with three important determinants of human health and survival: socioeconomic deprivation, physical environment and access to healthcare. More importantly, we have used robust measures that express how advantaged or disadvantaged small areas are in terms of the socioeconomic circumstances, physical environment, and in terms of access to healthcare. These measures were constructed based on sound theories and methods, which allow us to be confident about the study findings. Moreover, EDI and PT-MEDIX were built for other countries with which our results are internationally comparable. Statistically speaking, we have used robust spatial statistics that allowed us to account for the small number problem and extract the 'true' spatial pattern of old-age survival in Portugal. We also accounted for spatial autocorrelation, so that the associations we observed were not biased by the effect of some other confounding variable with similar spatial distribution as survival rates.

In conclusion, we found important spatial inequalities in the distribution of old-age survival across Portuguese municipalities. This geographical cleavage was partially explained by the factors we incorporate in the analysis. Socioeconomic deprivation was the most important determinant of old-age survival (especially among women). Further studies are needed to identify the unaccounted factors that might explain spatial differentials in old-age survival. Our results suggest policy makers should direct their efforts to tackle socioeconomic differentials between regions and guarantee equitable distribution of the healthcare resources.

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Authors' contributions
AIR designed the study, performed the statistical analysis and drafted the manuscript. EK performed the statistical analysis and helped to draft the manuscript. MSC and MFP helped designing the study, supervised the research, contributed to the interpretation of results and helped to draft the manuscript. All authors read and approved the final manuscript.

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5.5. The influence of socioeconomic, biogeophysical and built environment and old-age survival in a Southern European city (paper VI)

The influence of socioeconomic, biogeophysical and built environment on old-age survival in a Southern European city.

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ABSTRACT
Old-age survival is a good indicator of population health and regional development.We evaluated the spatial distribution of old-age survival across Porto neighbourhoods and its relation with physical (biogeophysical and built) and socioeconomic factors (deprivation). Smoothed survival rates and relative risks (RR) were estimated using Bayesian spatial models.
There were important geographical differentials in the chances of survival after 75 years of age. Socioeconomic deprivation strongly impacted old-age survival (Men: least deprived areas RR_1=1.307(1.052-1.632); Women RR_1=1.526(1.244-1.888)), explaining over 40% of the spatial variance. Walkability and biogeophysical environment were unrelated with old-age survival and also unrelated with socioeconomic deprivation, being fairly distributed through the city.
Key-words: residential characteristics; life expectancy; climate; socioeconomic status; land-use.

Introduction

Today, 52% of the world population, 76% of the European, and 63% of the Portuguese resides in urban areas (WB, 2014). During decades, urbanization was thought as synonym of human development and health (Stephens, 1996). However, recent studies have shown these settings hold important inequalities and harmful exposures (Vlahov et al., 2007; WHO/UN-HABITAT, 2010).

Residential segregation by socioeconomic position, race, ethnicity, can be observed in most urban settings (Kramer and Hogue, 2009). Residential segregation refers to the spatial separation of social groups within a certain geographical area (Massey and Denton, 1988). This socio-spatial process causes important environmental differences between neighbourhoods. For instance, affluent neighbourhoods are more likely to attract health-promoting facilities, such as healthy food shops, exercise facilities, services, commerce or cultural spaces, and to keep away hazardous exposures, such as pollutant industries or heavy traffic roads (Nogueira, 2010; Stephens, 1996; Woolf and Aron, 2013). Together with socioeconomic deprivation, social fragmentation and isolation represent another negative feature of urban living. But, evidence exists that living in walkable and mixed use neighbourhood might counteract these problems by improving social capital and by encouraging pedestrian dislocation (Hanibuchi et al., 2012; Leyden, 2003).

Urban residents are also generally exposed to poorer physical environments than their rural counterparts (Burkart et al., 2015; Marzluff et al., 2008; Vlahov et al., 2007) – high pollution levels, lack of natural and built greenspace, and frequent temperature extremes. All these influences have well-documented consequences on the health and survival of the populations (Burkart et al., 2015; Hajat et al., 2007; Shumake et al., 2013; Takano et al., 2002).

The social and environmental polarization that occurs in urban settings creates the 'perfect' ground to produce health inequalities then consubstantiated in neighbourhood-to-neighbourhood differences in mortality and life expectancy, as numerous studies have found (Borrell et al., 2014; Diez Roux et al., 2004; Domínguez-Berjón et al., 2010; Gotsens et al., 2013; Hoffmann et al., 2014; Mari-Dell'Olmo et al., 2015). Some of these studies have also observed that, although inequalities are universal, their magnitude varies greatly from setting to setting and seem to be considerably smaller in southern European cities (Borrell et al., 2014; Gotsens et al., 2013; Hoffmann et al., 2014; Mari-Dell'Olmo et al., 2015). The studies that have looked at the variations in health within Portuguese urban settings were restricted to the capital city, Lisbon (Borrell et al., 2014; Gotsens et al., 2013; Hoffmann et al., 2014; Mari-Dell'Olmo et al., 2015; Santana et al., 2015), and none of these studies have specifically addressed life expectancy and mortality of the eldest. Gains in life expectancy are currently driven by increases old-age survival (Kannisto, 2000; Mathers et al., 2014). Therefore old-age survival represents an important indicator of population health at the current stage of the epidemiological transition. Moreover, there are reasons to believe older populations might be particularly vulnerable to the characteristics of their immediate residential environment: climate extremes and air pollution have starker effects on the oldest (Hajat et al., 2007); older people might more frequently interact in the context of the neighbourhood; and might be more dependent on the local resources (shops, services, healthcare, recreation) (Diez Roux et al., 2004).

The fact that urban settings hold a variety of realities in a relatively small area makes them the ideal setting to study and monitor health inequalities, and to assay and implement actions against them. Moreover, because cities are human-designed places, constantly under construction, the identification health inequalities and their causes might more promptly generate a health policy response by the municipal governments (Collins and Hayes, 2010).

Therefore, the aim of this study is to characterize the spatial inequalities in old-age survival across the second most important urban area of Portugal, Porto, and to evaluate the role of socioeconomic and physical environmental factors in shaping those patterns. With that intent, three composite indicators will be used: the European Deprivation Index, to characterize the socioeconomic level of the neighbourhoods; the physical environmental deprivation index, to characterize biogeophysical environment (climate, pollution, greenness); and the walkability index to characterize the built environment in terms of availability and accessibility to destinations. The relations between these indicators will be explored too, namely we will assess whether or not most deprived areas are exposed to more detrimental environments.

Methods

Study area

Porto municipality is located in the northwest of Continental Portugal, comprising approximately 238,000 inhabitants in 2011 (INE, 2011), distributed across 41.7 km2.
Porto is limited by the Atlantic coast, and extends along the Douro River estuary. It is an industrial and port town inserted in the Porto Metropolitan Area, the second largest metro area of Portugal with roughly 1.3 million inhabitants.

Outcome

Life expectancy and mortality data at old ages is not disclosed at neighbourhood level and even if available estimating life expectancy for such small areas comes with well-documented problems – large standard errors and overestimation of life expectancy after 85 and 95 years of age (Eayres and Williams, 2004; Scherbov and Ediev, 2011).

Therefore, we had to derive a measure of old-age survival $\left(r_i = \frac{y_i}{n_i}\right)$ that expresses the probability of the people aged 75-84 years survive for an additional ten years, i.e., surpass the average life expectancy (Ribeiro et al., 2016). Where r_i is a ten-year survival rate, i =1,...,109 denotes area, the variable y_i represents the population aged 85-94 years old in 2011 and n_i the population aged 75-84 years old ten years before, in 2001.

Neighbourhoods

Population data for the above mentioned age groups was only available at census block group (CBG) level. As most covariates dated back to 2001, we used 2001 CBG as geographical unit (n=413 with an average population of 637 inhabitants). However, due to the boundary's changes of CBG between 2001 and 2011 and the presence of areas with very few or no residents aged 85-94 years in 2011, we aggregated the areas into 109 'super' CBG, which became our final units of analysis, from now on simply called neighbourhoods.

For this purpose, we used the SKATER algorithm (Spatial 'K'luster Analysis by Tree Edge Removal) (Assunção et al., 2006), implemented in R package 'spdep'(Bivand, 2015). SKATER is a regionalization approach that partitions a minimum spanning tree through a tree edge-removal procedure that focuses on edges with high dissimilarities (socioeconomic deprivation differences).

Covariates

Socioeconomic deprivation

The European Deprivation Index (EDI) was used to classify small areas according to their level of socioeconomic deprivation. The EDI is a transnational multivariate index developed for five European countries, France, England, Italy, Spain, and Portugal.

The construction of EDI took three steps, detailed elsewhere (Guillaume et al., 2015), and has included both individual and aggregated census data:

1) Construction of an individual indicator of deprivation, based on EU-SILC (EU-Statistics on Income and Living Conditions) information;

2) Identification of variables available both at individual level (EU-SILC) and at aggregated level (2001 national population census); and

3) Determination, at individual level, whether the set of variables selected at step 2 were associated with the indicator of individual deprivation created in step 1. The corresponding census variables were then included in the formula of EDI, whose final score resulted from the weighted sum of these variables. The weights were the regression coefficients that measured the association between the indicator of individual deprivation and the variables at individual level.

The index was normalized and then classified into ten classes (C_1 – least to C_{10} – most deprived). Cut-offs, theoretical deciles, were defined based on standard deviations to the overall mean, and they were then customized so that the classes included a balanced number of neighbourhoods (cut-offs=-1.28,-0.84, -0.52, -0.25, 0, 0.25, 0.52, 0.84, and 1.28). This approach avoids the well-known problems of using empirical quintiles, which assume homogeneity of risk within groups (Bennette and Vickers, 2012).

Physical environment

Measure of multiple physical environmental deprivation (Porto-MEDIx)
A measure of multiple physical environmental deprivation (Porto-MEDIx) was built for each of the 109 neighbourhoods of Porto following the principles used in the development of the nationwide Portuguese multiple physical environmental deprivation index (PT-MEDIx) (Ribeiro et al., 2015). The choice of the physical environmental variables to include in PT-MEDIX was based on extensive literature review and was then validated by checking if the selected variables were actually related to health.

However, because PT-MEDIx, was generated at municipality level (100 times larger than CBG), the spatial resolution of the previous datasets weren't adequate for creating an indicator at neighbourhood level. And, certain exposures included in PT-MEDIx, such as those related to the quality of the drinking water or industry proximity, are homogeneous across the city of Porto, hence irrelevant in this context. Porto-MEDIx was developed using alternative high resolution datasets that covered the following environmental domains: air pollution (particulate matter <10, nitrogen dioxide, carbon monoxide), climate (mean temperature of the coldest and warmest month), and greenspace availability (NDVI, Normalized Difference Vegetation Index). Included variables and procedures are summarized in Table 1.

Following the PT-MEDIx methodology, the neighbourhoods in the highest quintile of exposure received a punctuation of +1 for harmful factors and -1 for beneficial factors. The Porto-MEDIx of each neighbourhood resulted from the sum of these scores and, in the end, it ranged from -1 (least environmental deprivation) to +2 (most). A sample calculation is shown in Table 1.

Walkability index

Neighbourhood walkability is an indicator of local accessibility and destinations and it is composed by four elements (Frank et al., 2010). The ratio of retail building floor areas was not possible to compute in Porto, so our index incorporated the following variables:

- Residential density: obtained by calculating the density (number per area) of households within each neighbourhood. Data from the 2011 population and housing census was used for this purpose.
- Street connectivity: obtained by computing the density of street connection (number per area) within each neighbourhood. Only the streets that allowed pedestrian circulation were considered. Environmental Systems Research Institute, ESRI, Street map for ArcPad was used for this calculus.

Table 1 – Description of the datasets and neighbourhood-level measures derived for the selected environmental factors and exemplification of the calculation of the score of physical environmental deprivation

Environmental factor	Source	Description	Processing	Neighbourhood-level measure	Year(s)
Air Pollution	QUALAR (Online Database on Air Quality, Portuguese Environmental Agency)	Hourly measurements of Particulate Matter (PM_{10}), Nitrogen Dioxide (NO_2) and Carbon Monoxide (CO) for 12, 16 and 15 stations, respectively.	Decennial medians were computed. 30 m grids were generated by interpolation using inverse distance weighting (methods with the lowest root-mean squared error)	Mean of each pollutant	2001-2010
Climate	Moderate Resolution Imaging Spectrometer (MODIS) Montly Day-time Land surface temperature(Weiss et al., 2014)	Mean temperature of the warmest month (July) Mean temperature of the coldest month (January) minimum temperatures (ºC) 1 km grid	---	Mean of each climate variable	2001-2010
Green space	Landsat 8 Vegetation analysis images	Reflectance levels of the bands 3,4 (red, RED) and 5 (near infra-red, NIR) 30 meters grid	Normalized Difference Vegetation Index (NDVI) was derived according to the following formulae: (NIR-RED)/(NIR+RED)	Mean NDVI	2001-2010

In the highest quintile for:	Neighbourhood X		Neighbourhood Y	
	Yes/no	Punctuation	Yes/no	Punctuation
Air pollution? (PM_{10} or NO_2 or CO)	No	0	Yes	+1
Temperature? (warm or cold)	No	0	Yes	+1
Greenspace?	Yes	-1	No	0
PRT-MEDIX score		-1		+2

- Land-use mix: obtained by computing the entropy score for each neighbourhood, with values ranging from 0 (low land use diversity) to 1 (high land use diversity). Four land uses were considered, commercial, residential, recreational, and educational. Different datasets had to be used to ascertain land-uses: 2011 census data, European Environment Agency Urban Atlas land-use map, and points of interest from ESRI Street Map for ArcPad.

Each of these variables where standardized and the walkability score was obtained by summing them (no weighting). The walkablity index was then categorized in 10 classes following the approach adopted with socioeconomic deprivation.

Statistical analysis

To take into account the spatial autocorrelation and large variance of small areas, we used Hierarchical Bayesian spatial models. And to account for the fact that the effect of each variable class depends on the effect of the previous (ordered categorical covariate), and to allow for flexible slopes in the risk curve, flexible regression models were employed (Rue et al., 2005).

We assumed that the response variable, number of survivors (Y_i) in each ith area follows a Binomial distribution where p is an unknown survival rate and n the population aged 75-84 years old ten years before (equation 1).

$$Y_i \sim Bin\ (n, p) \qquad \text{(equation 1)}$$

$$logit(p) = \eta_i = j_i + f(x_i) + s_i \qquad \text{(equation 2.1)}$$

$$s_i = \tau(\sqrt{\varphi} * u_i + \sqrt{1-\varphi} * v_i) \qquad \text{(equation 2.2)}$$

where the mean is linked to a structured additive predictor η_i through a link-function logit. Here j_i is the linear effect of the covariate gender, $f(x_i)$ represent the non-linear/smooth effect of the covariates accounting for an interaction with gender, so that there is one non-linear smooth effect for each gender (equation 2.1). More specifically, $f(x_i) = e_{jl}$, where j denotes gender, and l denotes the classes of socioeconomic deprivation $(l = 1, \dots 10)$, Porto-MEDIx $(l = 1, \dots 4)$, and walkability index $(l = 1, \dots 10)$, which defined the knots of a first order random walk spline.

The s_i is the spatial effect, a reparametrization of the original BYM model (Besag et al., 1991), considered as a weighted sum of a structured scaled spatial effect u_i and an unstructured effect v_i (equation 2.2). The φ measures the amount of s_i attributed to the structured part. τ is the precision (inverse of the variance) and expresses the amount of variance associated to the spatial effect.

Model from equation 2.1 was our final model, but we have started with a null model, where we included only the spatial effect s_i, and then each covariate was successively introduced. The presence of interactions and correlations between the covariates was investigated as well.

Three different measures of goodness of fit were used (Deviance Information Criteria, Watanabe-Akaike information criterion and Conditional Predictive Ordinate) to compare models. The relative reduction in the variance of spatial effect (τ) was also evaluated to ascertain in what extent covariates contributed to explain the spatial variation of old-age survival.

Relative risk (RR) estimates and 95% credible intervals (95% CrI) were derived from their posterior means and quantiles. An RR would be considered significantly higher or lower if its 95% CrI does not include the value 1.

Posterior distributions were obtained using the Integrated Nested Laplace Approximation (INLA), which was implemented in the R INLA library (Rue et al., 2009).

Spatial patterns were characterized using the function excursions (Bolin and Lindgren, 2015). This method uses the posterior joint distribution computed from INLA and takes into account the dependence structure, allowing to accurately identify areas where the survival probability is greater/smaller than a certain threshold. In this study, we defined the mean old-age survival rates of each gender as threshold. A significance level of 0.05 was set up.

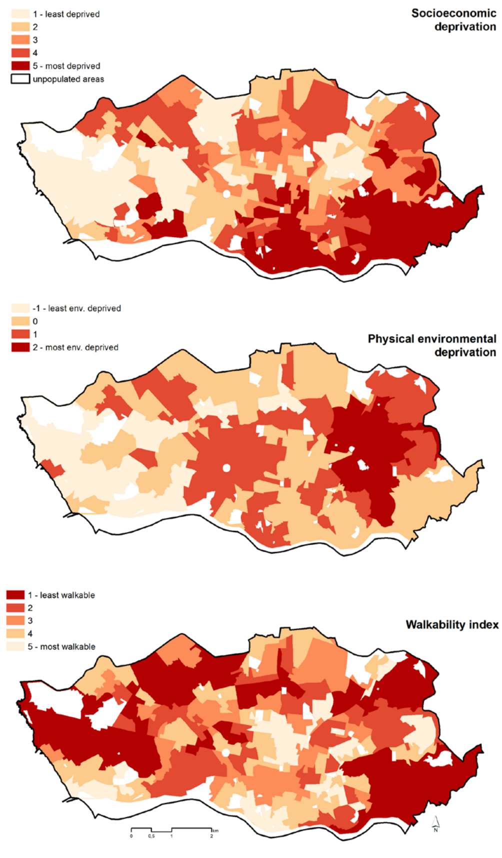

Figure 1. Spatial distribution of the covariates socioeconomic deprivation, physical environmental deprivation and walkability index across Porto neighbourhoods.

Results

Correlation between walkability, physical environment and socioeconomic deprivation

The spatial distribution of walkability, physical environment and socioeconomic deprivation is shown in Figure 1. We did not find signs of correlation between these covariates. There is no evidence of biogeophysical and built environment to be worst in most deprived areas, being the correlation coefficients near 0.02 and statistically non-significant.

Spatial patterns and statistical modelling

On average, in Porto, the proportion of 75-84 years old population that reached 85-94 was 34.9% (range: 22.0-54.2) among men and 45.7% (25.9-72.0) among women. These figures hide important spatial inequalities (more than a 2.5-fold difference in survival between areas). The spatial distribution of old-age survival is depicted on Figure 2. Dash-lined are the areas with significantly higher survival, and filled with dots are those with significantly lower survival. In general, the worst areas were located in the bottom center (the old-town) and in the eastern part of the city, and the best ones were concentrated in the western part of the city, coinciding with the patterns of socioeconomic deprivation seen in Figure 1.

Survival rates dropped linearly as socioeconomic deprivation increased. Survival rates of the least socioeconomically deprived areas averaged 42.0% among men and 55.7% among women; in the most deprived areas these were

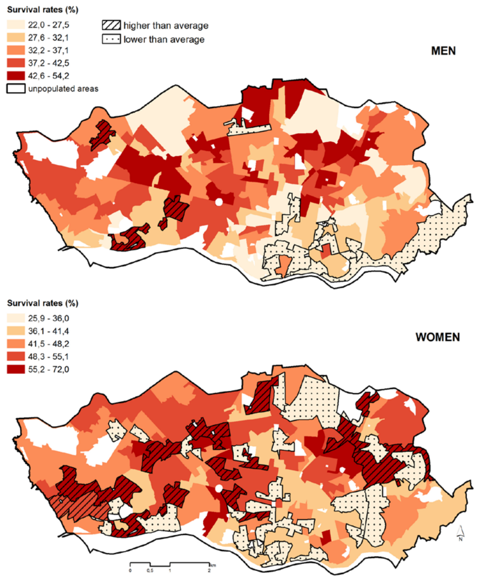

Figure 2. Spatial distribution of the posterior 10-year survival rates across Porto neighbourhoods for men and women.

Table 2. Association between old-age survival, socioeconomic deprivation, physical environmental deprivation and walkability index (Men)

	Model 1	Model 2	Model 3
	RR (95%CrI)[a] (socioeconomic deprivation only)	RR (95%CrI) (plus physical env. deprivation)	RR (95%CrI) (plus walkability index)
Socioeconomic deprivation			
1 (least deprived)	**1.321 (1.062-1.652)**	**1.309 (1.051-1.639)**	**1.307 (1.052-1.632)**
2	**1.237 (1.052-1.451)**	**1.230 (1.044-1.444)**	**1.226 (1.042-1.438)**
3	**1.318 (1.098-1.607)**	**1.314 (1.095-1.602)**	**1.324 (1.104-1.614)**
4	**1.248 (1.047-1.507)**	**1.244 (1.044-1.500)**	**1.242 (1.043-1.495)**
5	1.138 (0.963-1.359)	1.137 (0.963-1.358)	1.135 (0.961-1.352)
6	0.932 (0.779-1.105)	0.936 (0.782-1.109)	0.938 (0.784-1.113)
7	0.857 (0.712-1.024)	0.861 (0.716-1.030)	0.863 (0.718-1.031)
8	**0.785 (0.640-0.952)**	**0.789 (0.644-0.958)**	**0.790 (0.646-0.957)**
9	**0.742 (0.623-0.879)**	**0.745 (0.626-0.883)**	**0.742 (0.624-0.878)**
10 (most deprived)	**0.703 (0.575-0.854)**	**0.705 (0.576-0.857)**	**0.704 (0.577-0.854)**
Physical environmental deprivation			
-1 (least env. deprived)		1.018 (0.897-1.191)	1.018 (0.896-1.191)
0		0.971 (0.861-1.049)	0.966 (0.854-1.045)
+1		0.980 (0.877-1.063)	0.981 (0.879-1.066)
+2 (most env. deprived)		1.032 (0.914-1.217)	1.036 (0.916-1.222)
Walkability index			
1 (higher)			0.897 (0.723-1.065)
2			0.900 (0.753-1.034)
3			0.962 (0.839-1.091)
4			1.011 (0.894-1.163)
5			1.054 (0.931-1.251)
6			1.043 (0.926-1.203)
7			1.027 (0.902-1.175)
8			1.025 (0.891-1.177)
9			1.030 (0.893-1.189)
10 (lower)			1.069 (0.908-1.293)

[a]Relative Risks, RR, and corresponding 95% Credible Intervals, 95%CrI.
In bold, statistically significant results.

Table 3. Association between old-age survival, socioeconomic deprivation, physical environmental deprivation and walkability index (Women)

	Model 1	Model 2	Model 3
	RR (95%CrI)[a] (socioeconomic deprivation only)	RR (95%CrI) (plus physical env. deprivation)	RR (95%CrI) (plus walkability index)
Socioeconomic deprivation			
1 (least deprived)	**1.545 (1.258-1.916)**	**1.532 (1.246-1.901)**	**1.526 (1.244-1.888)**
2	**1.462 (1.259-1.707)**	**1.453 (1.249-1.698)**	**1.448 (1.248-1.688)**
3	**1.233 (1.034-1.463)**	**1.231 (1.033-1.460)**	**1.241 (1.044-1.471)**
4	1.118 (0.945-1.319)	1.114 (0.942-1.313)	1.110 (0.939-1.308)
5	1.036 (0.883-1.214)	1.036 (0.883-1.214)	1.031 (0.879-1.207)
6	0.966 (0.823-1.134)	0.967 (0.824-1.136)	0.967 (0.823-1.136)
7	0.917 (0.775-1.094)	0.920 (0.778-1.098)	0.921 (0.779-1.097)
8	**0.784 (0.648-0.943)**	**0.787 (0.651-0.946)**	**0.791 (0.656-0.950)**
9	**0.701 (0.597-0.821)**	**0.706 (0.601-0.827)**	**0.706 (0.602-0.826)**
10 (most deprived)	**0.637 (0.529-0.762)**	**0.640 (0.531-0.766)**	**0.641 (0.533-0.765)**
Physical environmental deprivation			
-1 (least env. deprived)		1.030 (0.916-1.211)	1.029 (0.914-1.209)
0		0.968 (0.863-1.041)	0.962 (0.855-1.036)
+1		0.992 (0.903-1.077)	0.995 (0.907-1.082)
+2 (most env. Deprived)		1.011 (0.891-1.160)	1.015 (0.894-1.166)
Walkability index			
1 (higher)			0.860 (0.690-1.022)
2			0.890 (0.754-1.017)
3			0.977 (0.866-1.111)
4			1.024 (0.915-1.181)
5			1.019 (0.896-1.167)
6			1.086 (0.967-1.282)
7			1.012 (0.885-1.143)
8			1.017 (0.885-1.143)
9			1.039 (0.909-1.191)
10 (lower)			1.102 (0.945-1.335)

[a]Relative Risks, RR, and corresponding 95% Credible Intervals, 95%CrI.

In bold, statistically significant results.

26.5% and 34.0% respectively. Regarding the Porto-MEDIx and the walkability index, areas with poorer biogeophysical and less walkable environments had nearly the same survival rates as those with better attributes.

After running the BYM model previous patterns were confirmed. Tables 2 and 3 show the RRs and corresponding 95%CrI for the relation between old-age survival and each of the covariates. There is a clear and linear relationship between old-age survival and socioeconomic deprivation in both genders (Men: least deprived areas RR_1=1.307(1.052-1.632); Women RR_1=1.526 (1.244-1.888)). The inclusion of socioeconomic deprivation in the model explained over 41% of the spatial variability. The addition of the remaining covariates did not alter that proportion significantly and the model adjustment parameters maintained almost unchanged or became slightly worst. The RRs associated with the categories of PRT-MEDIx and walkability were all statistically non-significant.

Discussion

This study aimed to characterize the spatial inequalities in old-age survival in Porto, located in the second largest metropolitan area of Portugal, and to understand how socioeconomic and physical environments shape those differentials. We observed clear spatial differences, and places with survival rates significantly higher/lower than expected. More than 41% of those differences can be attributed to the socioeconomic characteristics of the neighbourhoods. The effect of socioeconomic deprivation did not seem to be mediated by environmental exposures, as no relevant association between socioeconomic deprivation, physical environmental quality and walkability was observed. And, we also found that these measures that summarize physical environmental characteristics (built and biogeophysical) of the neighbourhoods were not associated with old-age survival at all.

In a previous study assessing spatial differentials in survival across Europe (Portugal inclusive) we found a nearly 2-fold difference between old-age survival rates in Portugal (Ribeiro et al., 2016). Within Porto differentials were even wider (2.5- to 2.8-fold difference), which corroborates the literature on the topic. Cities are unique settings with an high degree of residential segregation (WHO/UN-HABITAT, 2010). We were able to delimitate areas where survival rates were greater than expected through the computation of excursion sets. In general, the worst areas located in the bottom center (the old-town) and in the eastern part of the city, and the best ones concentrated in the western part of the city. The areas of significantly lower survival matched almost perfectly the locations of social housing and of "ilhas" (meaning "islands") (Vásquez and Conceição, 2015), whereas those of higher survival occur in the most affluent neighbourhoods. "Ilhas" are a unique type of housing of working classes, comparable to the back-to-back houses in UK, and usually of poor quality and high population density.

Socioeconomic deprivation was the main culprit of the observed geographical inequalities, accounting for over 41% of the spatial variability. As numerous studies and reports have been highlighting in the last years, socioeconomic factors are considered the fundamental causes of health. We cannot directly compare our findings with other studies, because the outcomes and covariates differ substantially. Still, our RRs are not considerably different from those reported on a series of studies on socioeconomic inequalities in all-cause (highest RR was 1.194 in Stockholm), injury-related (1.266 in Stockholm), avoidable (circa 1.3 in Helsinki) and cause-specific mortality (1.406 for chronic liver diseases in Stockholm) across different European metropolitan areas (Borrell et al., 2014; Gotsens et al., 2013; Hoffmann et al., 2014; Mari-Dell'Olmo et al., 2015). Specifically for cardiovascular disease mortality, Domínguez-Berjón and colleagues obtained RRs between 1.4 and 1.5 in Madrid neighbourhoods (Domínguez-Berjón et al., 2010). Lisbon area, in Portugal, was contemplated in some of those studies, but it seems there the socioeconomic gradients in mortality were rather small: RRs generally lower than 1.1 and often statistically non-significant. It surprises us that in Lisbon, larger in size and holding much more diverse population groups, the effect of socioeconomic deprivation was less clear. Yet, it might reflect the fact mortality differentials are shifting to older ages (Engelman et al., 2010); previous studies dealt with overall and premature mortality, whereas ours is restricted to the eldest. The geographical units of the research conducted in Lisbon were also much larger than ours, which might conceal some socioeconomic differentials.

Contrasting to what has been postulated, we did not find more deprived areas to have poorer biogeophysical environments or to be less pedestrian-friendly. This provides some clues about the mechanism involved in the socio-spatial patterning of old-age survival. According to the (neo)material model (Krieger, 2001), socioeconomic factors affect health because people from lower socioeconomic strain have lower financial capacity and also tend to reside in places with fewer community resources and exposed to harmful environments. Our results are not fully consistent with this theory, as no sign of unfair distribution in physical environment was found. Similar findings were reported in other European studies, suggesting in Europe environmental injustice is not as obvious as, for instance, in the USA (Deguen and Zmirou-Navier, 2010).

We did not find any relation between our index of physical environmental deprivation and old-age survival. The comparably smaller role of physical environment compared to socioeconomic factors is patent in numerous studies and reports (Domínguez-Berjón et al., 2010; Hood et al., 2015; Keon and Pépin, 2009). Porto has no serious air pollution problems and has a relatively good access to greenspaces, which might explain their limited influence on old-age survival. But, on the other hand, climate extremes (heat waves and cold spells) are quite frequent in the city and fatal among vulnerable groups such as seniors. With this in mind, we have looked at the sole impact of climate-related variables, but we did not find any association (results not shown). It is plausible that good material and social conditions (housing conditions, heating) are enough to supress harvesting effect of climate extremes (Klein Rosenthal et al., 2014).

Walkable and mixed use neighbourhoods are assumed to promote social interaction and health-related behaviours such as physical activity (Hanibuchi et al., 2012; Leyden, 2003; Takano et al., 2002; Van Holle et al., 2014), which in turn might affect old-age survival. In our study, we did not find any relation between walkability index and old-age survival. Truth is, even studies trying to measure the link between walkability and physical activity (a more proximal outcome) reached inconsistent or null associations (Van Holle et al., 2014). High street connectivity might also be related with traffic unsafety and negatively impact elderly well-being and behaviours. We have looked at the impact of each variable that composes the walkability index and we did not find any individually associated with survival (results not shown).

The main limitation of the study has to do with the Modifiable Areal Unit Problem (MAUP). A different arrangement of the geographical areas could lead to different spatial patterns and relative risks. Areas also varied in population size which might affect our results and condition our ability to identify areas with significantly lower/higher survival; excursions sets take into account the credible intervals which become wider as population counts decrease. Finally, there were potentially important determinants for old-age survival we were not able to account for, namely certain physical exposures such as noise and housing conditions, and social support.

The main strength of the study is that, to our knowledge, it is the first analysing the magnitude of the old-age survival inequalities across Porto neighbourhoods, which has obvious public health and political consequences. Second, we used multivariate covariates, to measure physical and socioeconomic characteristics of the neighbourhoods, whose construction was grounded on solid theory and on previously validated methods. Third, we have used robust statistical tools to identify patterns and measure associations. These methods generate smoothed estimates, avoiding random fluctuations typical of small spatial units (and populations). Frequently variables that explain variability in the response, including possible confounding variables, also vary spatially (Paciorek, 2010). Bayesian spatial models allowed us to model the spatial structure of old-age survival and reduce confounding bias resultant from any unaccounted variables, although we handled part of it by including three key multidimensional explanatory variables.

In summary, we found substantial intra-urban inequalities in the chances of survival later in life. A large share of the spatial variability was explained by the socioeconomic characteristics of the neighbourhoods. Physical environment, biogeophysical and built, were unrelated with old-age survival and did not seem to be mediating the socioeconomic effects. These findings demonstrate there is a high degree of socio-spatial segregation within Porto, suggesting the socioeconomic differentials in southern European cities might not be as small as usually thought. Policy makers should then make an effort to tackle these pockets of low survival and poverty.

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Authors' contributions
AIR designed the study, performed the statistical analysis and drafted the manuscript. EK performed the statistical analysis and helped to draft the manuscript. RA and HT contributed to the interpretation of results, helped to draft the manuscript and developed, together with AIR and MFP, the walkability index. MSC and MFP supervised the research, contributed to the interpretation of results and helped to draft the manuscript. All authors read and approved the final manuscript.

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5.6. Physical activity-friendly neighbourhood among older adults from a medium size urban setting in Southern Europe (paper VII)

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Physical activity-friendly neighbourhood among older adults from a medium size urban setting in Southern Europe

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ABSTRACT

Objective. In this cross-sectional study, we examined the relationship between socio-environmental characteristics of neighborhood of residence and the frequency of leisure-time physical activity (LTPA) among older adults from Porto (Portugal).

Method. Data from EpiPorto – a prospective adult cohort study from Porto (Portugal) – were used. Only adults aged ≥65 at baseline (1999–2003) were included (n = 580). We used a Geographic Information System to objectively measure the neighborhood characteristics and Generalized Additive Models to estimate their effect on participation in LTPA (none vs. some reported) and frequency of LTPA (min/day).

Results. 62% of the participants reported no LTPA. Active elderly spent on average 38 (women) and 67 (men) minutes per day exercising. Neighborhood characteristics were unrelated to whether older people exercised or not. However, among active individuals, distance to the nearest destination ($\beta = -0.154$, $p = 0.016$), in women, and distance to the nearest park, in men (−0.030, 0.050), were predictors of LTPA frequency.

Conclusion. There was almost no association between neighborhood characteristics and whether older adults engaged in LTPA or not, but among those that did engage, neighborhood characteristics were associated with increased frequency of LTPA. The promotion of well distributed destinations and parks might improve physical activity levels among the elderly.

Introduction

Along with a healthy diet and psychosocial well-being, physical activity (PA) is a major determinant for successful aging (Gremeaux et al., 2012). International guidelines among older adults recommend 150 min of moderate–vigorous PA per week (WHO, 2010) but even light intensity PA is an important predictor of survival (Dogra and Stathokostas, 2012). Still, the majority of older people report sedentary lifestyles.

Several motivators and barriers may influence an older person's PA (Schutzer and Graves, 2004). While there has been a recent plethora of studies on the associations between PA and neighborhood characteristics, these focused predominantly on children, adolescents and working-age adults. But changes in functional and cognitive capacity, reductions in income and increasingly limited spaces for activity make seniors more vulnerable to the effects of local environment on health and related behaviors (Kawachi and Berkman, 2003).

Many environmental correlates of PA have been mooted. However, systematic reviews have found inconsistent results. The association between neighborhood attributes and PA is by no means proven (Cunningham and Michael, 2004; Koeneman et al., 2011; McCormack and Shiell, 2011). It is also likely that associations will vary by gender, and that gender differences may interact with age. Firstly, the older individuals are, the lower their mobility. Secondly, the use of space is highly dependent on social constructs. For instance, women appear to be more vulnerable to the neighborhood effects (Stafford et al., 2005). In addition, social environment seems particularly important in women,

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whereas physical environment predominantly affects men (Kavanagh et al., 2006).

However, several weaknesses can be pointed out in most of the studies exploring the relationships between environment and health-related behavior: 1) self-reported bias because of the use of subjective measures about neighborhood environment; 2) focus on large heterogeneous urban settings, disregarding smaller city neighborhood effects may be different; and 3) preference for multilevel models that contemplate neither the inter-area dependency (Chaix et al., 2005) nor the modifiable area unit problem, when results are influenced by the size/shape of the administrative divisions (Openshaw, 1984).

Our study addresses a current gap in the literature by examining, using a cross-sectional design, the relationship between socio-environmental variables of neighborhood of residence and the frequency of leisure-time physical activity (LTPA) among older adults from Porto (Portugal).

Methods

Setting

Located in the northwest of Continental Portugal, Porto municipality had approximately 260,000 inhabitants in 2001(INE, 2001) distributed across 41.7 km^2. It is near the Atlantic coast, along the Douro River estuary. Historically, Porto is an industrial and port city that competes with Lisbon in terms of economic power.

Participants

The EpiPorto Cohort encompasses a representative sample of adults aged 18–92 years living in Porto. Baseline evaluation was conducted from 1999 to 2003. Participants were recruited by random digit dialing using households as the sampling frame. After assessing the number and age of the residents of each household, a simple randomization was applied to select one eligible person among the permanent adult residents. In the case of a refusal, no replacement was permitted. The response rate was 70%, resulting in a total of 2485 participants (Santos and Barros, 2003).

The local ethics committee approved the study protocol. The study was carried out according to the Helsinki Declaration and all participants completed the informed written consent form. A Geographical Information System (GIS) was used to georeference addresses. For the present study, only adults aged 65 or more at baseline were included (N = 648). Three (0.5%) were excluded because of bad quality of address data.

The Mini Mental State Examination (MMSE) was used to screen for cognitive impairment. Taking into account that MMSE is highly affected for educational levels and no consensual cut-off values exist (Schmand et al., 1995), individuals with scores below the 5th percentile were excluded according to education-adjusted cut-off values: >14 for 0–2 years of schooling, >21 for 3–4 years (the former levels of obligatory education in Portugal), >23 for 5–8 years and >25 for more than 8 years of schooling. Accordingly, 35 participants (5.4%) were excluded, reducing the sample to 610 individuals.

Leisure-time physical activity assessment

LTPA was evaluated using the EpiPorto Physical Activity Questionnaire to measure time and intensity of a wide range of activities, such as rest, transport, work, household and leisure, which includes walking and organized sports (Camões et al., 2010). Time spent (min/day) in LTPA was available for 580 individuals, our final sample. Participants were classified into two categories: inactive (no LTPA reported) and active (some LTPA even if insufficient).

Compared with the final sample, subjects with missing data on LTPA were older, less educated and had been more frequently employed in manual occupations ($p < 0.001$).

Individual variable assessment

Individual characteristics were obtained through structured questionnaires and variables established as important predictors of LTPA were included as confounders: age; marital status; educational attainment (number of schooling years); previous occupation (re-categorized into manual and non-manual workers); smoking status (smoker, occasional smoker, non-smoker and ex-smoker); comorbidities (absence or presence of at least one of the following conditions — cardiovascular, respiratory, osteoarticular and musculoskeletal disorders, cancer, depression, cirrhosis and hypo/hyperthyroidism); residence in Porto for 20 years or more (yes/no); and body mass index (discretized according to the World Health Organization, WHO, cut-offs).

Socio-environmental variable assessment

Neighborhood characteristics included as independent variables in the statistical analysis were: socioeconomic status (SES) and population density of the census tract of residence, distances to the nearest park, sport space, destination and sea/riverside, density of street intersections and bus stops and average land gradient within 200 m (adopted as the walkable distance for older individuals, simply referred to below as neighborhood) around participant's residence. Since individual data refers to baseline evaluation (1999–2003) all neighborhood characteristics were collected for 2001.

Latent class analysis was used to model SES, from a set of socioeconomic indicators at census tract level, related to age and education/occupation of residents and housing characteristics obtained from Statistics Portugal (INE, 2001) (Alves et al. [results not published yet]). Three discrete classes of SES were identified for Porto — from the least to the most deprived. Census data were also used to compute population density.

Park boundaries and entrances were obtained from the city council digital maps. Public sports spaces were georeferenced using a Global Positioning System. Sport spaces were classified into those typically preferred by men (n = 71, football, volleyball, walking, tennis, table tennis, boccia, swimming, golf, athletics and cycling); or women (n = 25, volleyball, walking, tennis, table tennis, boccia, swimming, golf, athletics and cycling). This classification was based on local Portuguese reports and international studies, which documented a clear mismatch between sports preferences in older women and men (Marin, 1988; Salvador et al., 2009; Warde, 2006).

Additionally, the position of common destinations was assessed (using exhaustive lists and Google Earth imagery): public medical care services (hospital and health centers), places of worship (churches and cemeteries), cultural infrastructure (libraries and museums), shopping centers and elementary schools (accessed for leaving and picking up grandchildren).

Distances to parks, sport spaces, destinations and sea/riverside were calculated by the shortest street route from residence to the nearest feature.

Bus stop locations were obtained from STCP (Society for Collective Transports of Porto) and average land gradient (%) was computed using a digital elevation model (scale = 1:25,000) from the Army Geographical Institute.

The location of the participant's residence and socio-environmental attributes are depicted in Fig. 1.

Statistical analysis

Descriptive statistics were computed for all variables, by sex and degree of participation in LTPA. Mann–Whitney U and Chi-square tests were employed to compare distributions and proportions — differences were confirmed at a significance value ≤0.05.

For data modeling, LTPA was used as a dependent variable and individual and neighborhood characteristics as covariates. Firstly, the null hypothesis that LTPA doesn't depend on the spatial location of an individual's residence was tested. Secondly, univariate analysis was conducted and all covariates with p-values ≤0.10 were included in the initial multivariate model. Then, each covariate was removed step by step until the final adjusted model was attained, eliminating consecutively those with the highest p-values. The final model included only covariates with p-values ≤0.05 and a function (thin plate spline) applied on the coordinates of each participant's residence. The presence of interactions was evaluated by including interaction terms between gender/marital status and area variables.

Two phases of models were built to test the hypotheses that 1) neighborhood characteristics were related to participation in LTPA and 2) neighborhood characteristics affect the time spent on LTPA among already-active persons. The first model (Eq. (1)) included the whole sample and assessed LTPA as a dichotomous variable (active/inactive). The second (Eq. (2)) contained only active individuals and assessed LTPA as a continuous variable (min/day). Given its skewed distribution, the variable LTPA was log-transformed. The equations are presented below:

$$\ln(y_i) = \beta_0 + \sum \beta_k x_{ik} + f(north_i, east_i) + e_i \tag{1}$$

$$z_i = \beta_0 + \sum \beta_k x_{ik} + f(north_i, east_i) + e_i \tag{2}$$

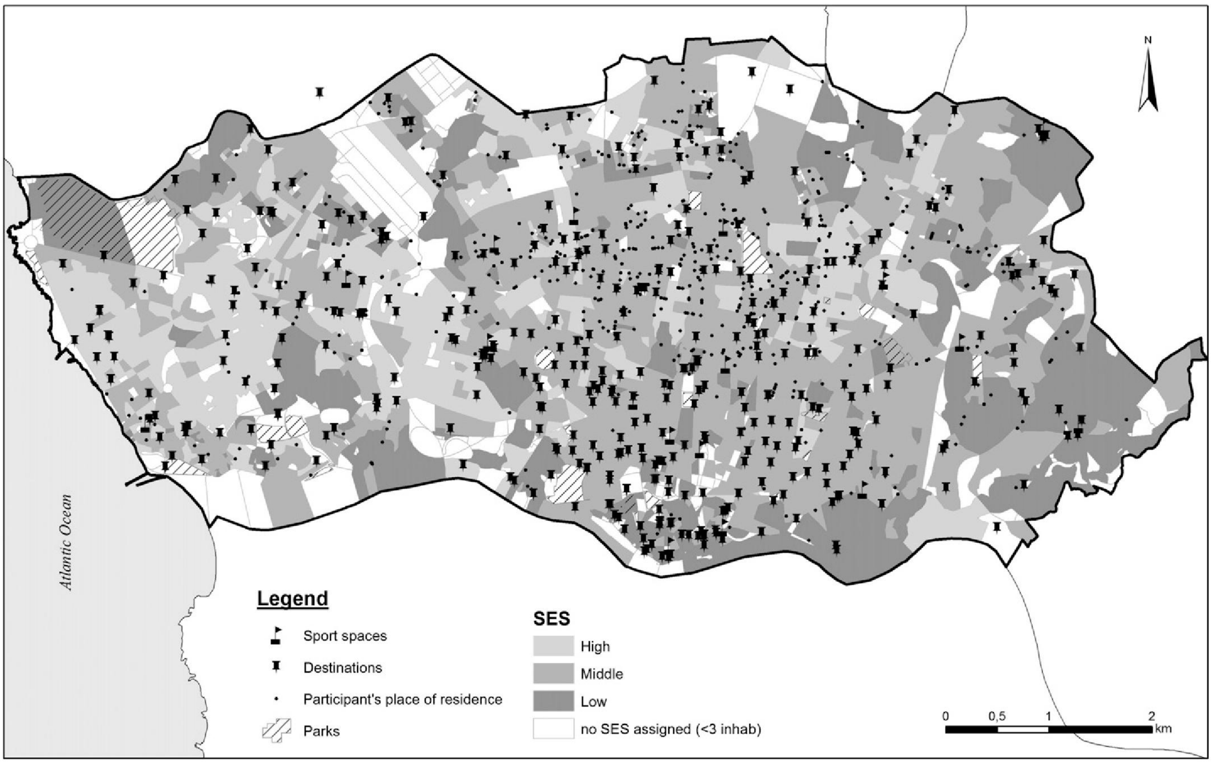

Fig. 1. Spatial distribution of the participant's residences and built and socio-environmental features (Porto, 1999–2003).

where y_i is any LTPA, z_i is the logarithm of the time spent on LTPA, βs are the coefficients of the model, x_{ik} are the explanatory variables, $f(north_i, east_i)$ is a smooth function of the coordinates and e_i are the residuals.

Additionally, the shape of significant relationships was estimated using thin plate splines and graphically represented. Due to the presence of interactions between sex and some neighborhood characteristics, sex-stratified models were built.

All analyses were conducted in R using the packages 'mgcv' (Wood, 2009), 'spatstat' (Baddeley and Turner, 2013) and 'spdep' (Bivand, 2013). ArcMap was used to georeference addresses, assess neighborhood characteristics, calculate routes and map results.

Results

Descriptive statistics

Table 1 shows the demographic and neighborhood socio-environmental characteristics of the study sample.

From the total sample of 580 participants (57.9% women), 62.4% reported no LTPA. The mean age was around 72 years old for both sexes. Most of the participants were married; among women, there were a large proportion (39.3%) of widows. Contrary to men, women were more likely to have been previously employed in manual professions. The mean number of schooling years was 5 and 7 years, respectively for women and men ($p < 0.001$). Overweight was the most common BMI condition but gender differences were found ($p < 0.001$). While there were very few female smokers, only 34.8% of the men reported they had never smoked ($p < 0.001$). Around 60% of the women and 32% of the men reported at least one illness ($p < 0.001$).

Mean distance to the closest park, sport space and destination was below 1 km, reflecting equal opportunities to Porto residents. The average street intersection density was 3 nodes per hectare and participants had on average 3 bus stops around their residence. The average distance to the coast or riverside was more than 3 km. The majority of participants lived in medium SES neighborhoods. Distance to suitable sport spaces was greater ($p < 0.001$) for women: around 800 m to the nearest feature. With the exception of neighborhood population density – lower among the active – no other neighborhood or individual variable differed significantly between active and inactive participants.

Among active individuals, the mean LTPA was 38.4 (women) and 66.9 (men) minutes per day. Only 11% of the females and 8% of the males fulfilled the WHO recommendations for PA (150 min per week of moderate-to-vigorous intensity).

Missing values were rare — a maximum of 13 cases for BMI.

Generalized Additive Models

There was no spatial autocorrelation in the distribution of participation in LTPA (either active/inactive or min/day). Thus, the spatial smoothing term was excluded from the models.

Results from the first phase of modeling (logistic regression with all participants, predicting any LTPA) showed that neighborhood characteristics – apart from population density in men (OR $= 0.995$, $p = 0.013$) – had a limited effect on LTPA among older people. The model had a poor explanatory capability: 9.4% (men) and 6.0% (women) of the variability of the response (results not shown).

Table 2 shows the unadjusted and adjusted results of the second phase of modeling (already-active persons). Unadjusted analysis (Model 1) revealed a significant negative influence of neighborhood SES in LTPA in men and a positive effect among women. Distance to the nearest destination was negatively associated with women's LTPA.

After adjustment for potential confounders (Model 2), distance to destinations remained significant with women, with a negative effect on LTPA ($\beta = -0.1536$, $p = 0.016$). For every increase of 100 m in the distance to the nearest destination, the time spent in LTPA reduced

Table 1
Characteristics of the participants (Porto, 1999–2003) according to participation in LTPA (inactive or active).

	Total (N = 580)		Inactive (N = 362)		Active (N = 218)	
	Women (N = 336)	Men (N = 244)	Women (N = 232)	Men (N = 130)	Women (N = 104)	Men (N = 114)
	Mean (SD)[a] or %	Mean (SD) or %	Mean (SD) or %	Mean (SD) or %	Mean (SD) or %	Mean (SD) or %
Age (years)	71.8 (5.2)	2.0 (5.4)	71.9 (5.4)	71.8 (5.7)	71.5 (4.9)	72.3 (4.9)
Marital status[*]						
Married	44.6	86.5	44.0	87.7	46.2	85.1
Single	9.8	0.4	9.5	0.8	10.6	0.0
Widowed	39.3	9.8	40.9	8.5	35.6	11.4
Divorced/separated	6.3	3.3	5.6	3.1	7.7	3.5
Education attainment (no. years)[*]	5.0 (3.9)	6.8 (4.2)	4.5 (3.5)	7.1 (4.6)	6.2 (4.5)	6.6 (3.7)
Type of occupation[*]						
Non-manual	29.8	61.7	27.2	62.8	35.6	60.5
Manual	70.2	38.3	72.8	37.2	64.4	39.5
Residence in Porto (>20 years)	82.1	81.1	80.6	79.2	85.6	83.3
Comorbidities[*]						
No	39.9	67.6	42.2	72.3	34.6	62.3
Yes	60.1	32.4	57.8	27.7	65.4	37.7
Body mass index[*]						
Underweight (<18.5)	0.3	1.2	0.5	0.8	0.0	1.8
Normal (18.5–24.9)	17.5	33.6	15.8	31.0	21.2	36.6
Overweight (25.0–29.9)	47.5	46.5	46.4	48.1	50.0	44.6
Obese (≥30.0)	34.7	18.7	37.4	20.2	28.8	17.0
Smoking habits[*]						
Smoker	1.2	14.8	0.9	15.4	1.9	14.0
Occasional smoker	0.3	0.8	0.4	0.8	0.0	0.9
Non-smoker	93.7	34.8	93.9	33.8	93.3	36.0
Ex-smoker	4.8	49.6	4.8	50.0	4.8	49.1
LTPA[c] (min/day)[*]	11.9 (29.2)	1.3 (53.0)	0	0	38.4 (41.8)	66.9 (60.3)
Met WHO recommendations (150 MVPA min/week)[d]	3.3	33.7	0.0	0.0	10.6	7.9
Distance to the nearest park (hm)	8.3 (5.7)	88.6 (5.6)	8.1 (5.4)	8.7 (5.3)	8.6 (6.3)	8.4 (5.9)
Distance to the nearest suitable sport space (hm)[*]	8.1 (4.2)	55.0 (2.9)	8.0 (4.1)	5.2 (3.0)	8.2 (4.6)	4.9 (2.9)
Distance to the nearest destination (hm)	2.3 (1.5)	23.3 (1.4)	2.3 (1.5)	2.4 (1.5)	2.2 (1.4)	2.3 (1.4)
Distance to the sea/riverside (hm)	30.5 (11.3)	330.8 (10.2)	30.9 (11.0)	31.1 (10.0)	29.6 (11.9)	30.4 (10.4)
Population density (inhabit/ha)[#]	121.9 (73.6)	1123.6 (78.9)	124.7 (76.1)	134.1 (81.2)	115.8 (67.6)	111.6 (74.8)
Intersection density (nodes/ha)[e]	3.4 (1.8)	33.3 (1.9)	3.4 (1.7)	3.4 (1.9)	3.4 (2.0)	3.2 (1.8)
Bus stops[e]	3.3 (1.9)	33.2 (1.9)	3.4 (2.0)	3.2 (1.9)	3.1 (1.8)	3.3 (1.8)
Land gradient (%)[e]	2.6 (1.5)	22.5 (1.4)	2.6 (1.5)	2.4 (1.3)	2.5 (1.6)	2.5 (1.5)
Neighborhood SES[b]						
1 — least deprived	18.5	221.3	16.8	24.6	22.1	17.5
2 — medium deprived	64.9	660.7	65.5	60.0	63.5	61.4
3 — most deprived	16.7	118.0	17.7	15.4	14.1	21.1

[a] SD = standard deviation.
[b] SES = socioeconomic status.
[c] LTPA = leisure-time physical activity.
[d] WHO = World Health Organization, MVPA = moderate-to-vigorous physical activity.
[e] Within 200 meter circular buffer.
[*] $p \leq 0.05$ comparing men and women.
[#] $p \leq 0.05$ comparing active and inactive.

by 14.2% ($(1 - e^{\beta 1}) \times 100$). Among men, it was distance to parks that showed a slightly detrimental effect on LTPA ($\beta = -0.0298$, $p = 0.050$): for every 100 meter increase in distance, LTPA decreased by 2.9%. No other variables were significantly associated. Overall, the models accounted for 12.6% (women) and 14.5% (men) of the variability in LTPA.

We examined the functional form of the associations shown in Table 2 and detected a linear dose–response relationship between LTPA and distance to destinations among women (Fig. 2). In men, however, the relationship was curvilinear, less clear and only significant up to 500 m (Fig. 2).

Discussion

We examined the relationship between several objectively measured neighborhood characteristics and the frequency of LTPA in older people from Porto. Neighborhood characteristics were unrelated to whether they were physically active or not. When analysis was restricted to those active in some way, only distance to the nearest destination, in women, and distance to the nearest park, in men, were (negatively) associated with LTPA.

The direction of associations between LTPA and environmental characteristics was as expected and in line with findings from other studies. Proximity to shops, schools, cultural sites and places of social interaction may encourage older adults to perform PA, and has been associated with different types of PA (Inoue et al., 2011; Michael et al., 2006; Nagel et al., 2008; Nathan et al., 2012; Siu et al., 2012; Van Cauwenberg et al., 2012). We observed this association only for women and this, too, is echoed in the literature (Inoue et al., 2011; King et al., 2005; Van Dyck et al., 2012). Older women, especially in traditional societies such as Portugal, are usually responsible for domestic tasks – shopping, leaving grandchildren at school – and involved in

Table 2
Association between daily minutes spent in leisure-time physical activity (log-transformed) and neighborhood characteristics, stratified by sex (Porto, 1999–2003).

	Model 1[a]				Model 2[b]			
	Women		Men		Women		Men	
	Coefficient	p-Value	Coefficient	p-Value	Coefficient	p-Value	Coefficient	p-Value
Distance to the nearest park (m)	−0.0265	0.051	−0.0230	0.124	–	–	−0.0298	0.050
Distance to the nearest sport space (m)	0.0055	0.770	0.0219	0.477	–	–	–	–
Distance to nearest destination (m)	−0.1675	0.004	0.0459	0.468	−0.1536	0.016	–	–
Distance to the sea/riverside (m)	−0.0051	0.482	−0.0042	0.626	–	–	–	–
Population density (inhabit/ha)[c]	−0.0015	0.231	0.0003	0.788	–	–	–	–
Street intersection density (nodes/ha)[c]	−0.0329	0.455	0.0098	0.842	–	–	–	–
Bus stops[c]	−0.0233	0.625	0.0319	0.509	–	–	–	–
Land gradient (%)[c]	−0.0029	0.958	−0.0044	0.940	–	–	–	–
Neighborhood SES[d]					–	–	–	–
1 — least deprived	Ref		Ref					
2 — medium deprived	−0.2436	0.245	0.4390	0.066				
3 — most deprived	−0.6442	0.026	0.2161	0.445				

[a] Univariate analysis.
[b] Multivariate analysis, adjusted for age, educational attainment, marital status, type of occupation, comorbidities, BMI and smoking habits.
[c] Within 200 meter circular buffer.
[d] SES = socioeconomic status.

church activities. It is thus reasonable to expect that the vicinity of those destinations might increase PA.

The association between proximity to parks and LTPA among men has been explored in other studies (Hanibuchi et al., 2011; Li et al., 2005; Siu et al., 2012). In our work, the distance from parks was negatively associated with PA among men, but the strength of this relationship was weak, indicating its contribution might be minor. Indeed, the literature finds the association for men to be relatively inconsistent and perhaps dependent on park attributes, and that associations for women are more usually absent (Hall and McAuley, 2010; Inoue et al., 2011; Nagel et al., 2008; Strath et al., 2012; Van Cauwenberg et al., 2012). Several studies have noted that the use of green space differs by gender: women tend to visit public parks less frequently and avoid them if they are unsafe and/or neglected. Men, in contrast, report fewer concerns about safety and tend to visit them often (Foster et al., 2004; O'Brien, 2005; Richardson and Mitchell, 2010). We could not assess the effect of public safety or quality of parks on LTPA, due to absence of data. However, since Porto is known to be a rather secure city, public safety might not be a key variable.

The absence of a relationship between LTPA and distance to sport facilities diverges from other studies (Cerin et al., 2012; Giehl et al., 2012; Li et al., 2005). The lack of association in our study might result from a preference among Porto's older population for walking as PA, as in other settings (Cohen-Mansfield et al., 2004), thus not requiring exercise facilities. However, our data did not allow us to distinguish walking from other forms of PA.

No association between LTPA and street connectivity and density of bus stops was observed, which contrasts with studies where older people living in highly connected areas have been found to be more active (Hall and McAuley, 2010; Li et al., 2008). However, many other studies found no association (Hanibuchi et al., 2011; Nagel et al., 2008; Strath et al., 2012).

Land gradient and distance to sea or riverside had no effect on LTPA, but population density seemed to slightly inhibit PA. To our knowledge only one study has found such a negative relationship before (Tsunoda et al., 2012), while others found no clear association (Gomez et al., 2010; Hanibuchi et al., 2011). Unmeasured characteristics associated with dense urban areas – noise, unsightliness, traffic and crime – could explain our findings. These features have been examined elsewhere, and have been found to have a negative association with PA (Gomez et al., 2010; Kremers et al., 2012; Li et al., 2005; Nagel et al., 2008; Strath et al., 2012; Van Cauwenberg et al., 2012).

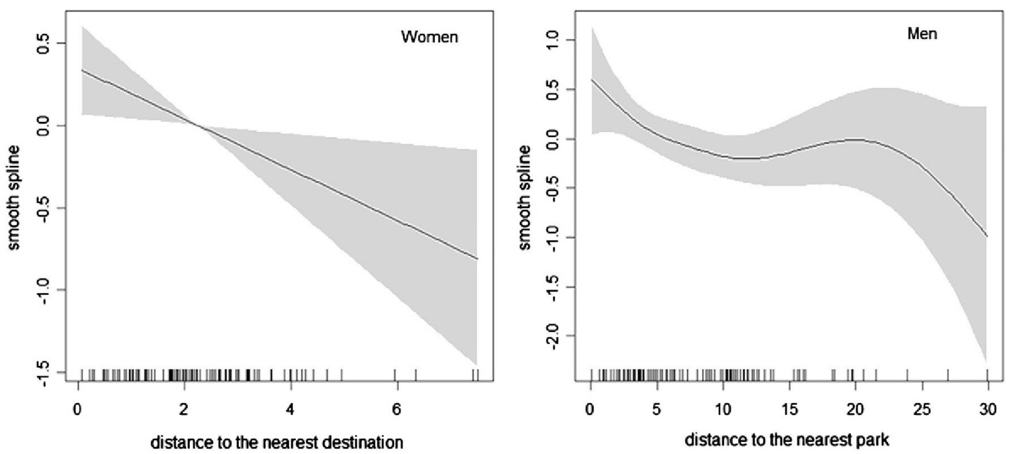

Fig. 2. Effect of distance to the nearest destination (women) and park (men) on the frequency of leisure-time physical activity (Porto, 1999–2003). Solid line represents the smooth term estimating the effect of distances (hm) on the frequency of leisure-time physical activity; gray shade limits the 95% confidence interval.

Surprisingly, we found no association between neighborhood SES and LTPA frequency, and no interaction between neighborhood SES and other neighborhood characteristics. Comparisons with other studies are difficult because the role of neighborhood SES on older individuals' PA has been poorly explored and area-level SES measurements vary greatly between studies and settings. Perhaps inevitably then, mixed results are found throughout the literature (King et al., 2005; Michael et al., 2010; Siu et al., 2012; Van Dyck et al., 2010). Furthermore, it is possible that our measurement of area SES did not capture all dimensions of this broad construct, despite being a multidimensional classification.

Limitations

Nonetheless, study weaknesses need to be acknowledged. Firstly, the cross-sectional design prohibited investigations of causality. Secondly, it relied on self-reported frequency of LTPA. Systematic bias in recollection or reporting remains a possibility. Thirdly, only frequency of PA was measured. There was no discrimination of PA's modalities, only of groups of activities based on energy expenditure. However, the EpiPorto PA Questionnaire was based on a well-established questionnaire (European Prospective Investigation into Cancer and Nutrition) and the validation procedure showed that it is a valid and reproducible instrument for assessing PA among adults (Camões et al., 2010). Fourthly, the study was restricted to a single urban setting with unique characteristics – relatively homogeneous and compact urban design and an equal distribution of socio-demographic characteristics among its inhabitants – which certainly limits the generalizability of the results. Lastly, although we did assess a large number of neighborhood characteristics, we could not include important factors, such as crime, traffic and social support. Likewise, due to data unavailability, we did not incorporate subjective measures of urban environment, which, as seen in previous studies (Inoue et al., 2011; Strath et al., 2012; Van Cauwenberg et al., 2012), might act as important barriers/motivators of PA among older adults and could have contributed to increase the amount of the variability in LTPA explained by our models.

Strengths

The study has several strengths. The use of objective measures to characterize neighborhood environment reduced the risk of bias associated with subjective measures, frequently seen as a cause of inconsistencies between studies (Koeneman et al., 2011). Our study also captured a wide range of attributes from sport infrastructures to physical environment, maximizing the chance that important correlates were included. Additionally, it was based on a large well-characterized population-based cohort. Being one of the first studies on older population in Southern Europe and the first in Portugal, this represents an important strength, because research should cover diverse regions in order to confirm findings and analyze its generalization potential. Finally, our work fits international and, particularly, European Commission demands in terms of scientific research: Horizon 2020 (framework program for research and innovation) is pushing member states to target their investigation at the field of active aging and age-friendly environments.

Conclusions

Proximity to shops, cultural sites, places for social interaction and, weakly, parks was associated with increasing time spent on LTPA among the elderly who already participate in PA. However, in this setting, neighborhood characteristics did not define whether older adults were active (some PA) or inactive (no PA at all). From a public health perspective, promoting well distributed destinations and parks could increase the (currently small) percentage of older people who meet PA recommendations. Nevertheless, there is a lack of consensus as to the environmental correlates of PA claims for more longitudinal studies and standardized/validated measures of PA and neighborhood attributes. Given that the pressure over health and social provision systems has been aggravated as demographic aging advances, more attention should be drawn to primary prevention, namely through urban planning interventions.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

Acknowledgments

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5.7. Distance to parks and non-residential destinations influences physical activity of older people, but crime doesn’t: a cross-sectional study in a southern European city (paper VIII)

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RESEARCH ARTICLE Open Access

Distance to parks and non-residential destinations influences physical activity of older people, but crime doesn't: a cross-sectional study in a southern European city

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Abstract

Background: Physical activity (PA) has numerous health benefits, but older adults live mostly sedentary lifestyles. The physical and social neighborhood environment may encourage/dissuade PA. In particular, neighborhood crime may lead to feeling unsafe and affect older adults' willingness to be physically active. Yet, research on this topic is still inconclusive. Older population, probably the age group most influenced by the neighborhood environment, has been understudied, especially in Southern Europe. In this study, we aimed to analyze the association between leisure-time physical activity (LTPA) in older adults and objective crime, alongside other neighborhood characteristics.

Methods: We obtained data from a population-based cohort from Porto (2005–2008) to assess LTPA. Only adults aged 65 years or more were included ($n = 532$). A Geographic Information System was used to measure neighborhood characteristics. Neighborhood crime was expressed as crime rates by category (incivilities, criminal offenses with and without violence and traffic crime). Neighborhood characteristics such as socioeconomic deprivation, land gradient, street density, transportation network, distance to parks, non-residential destinations and sport spaces were also included. Generalized Additive Models were fitted to estimate the association between neighborhood characteristics and the participation (being active vs. inactive) and frequency (min/day) of LTPA.

Results: Forty-six percent of the men and 61 % of the women did not engage in any kind of LTPA. Among the active participants, men spent on average 50.5 (35.2 Standard Deviation, SD) min/day in LTPA, whereas the average among women was 36.9 (35.1 SD) min/day ($p < 0.001$).
Neighborhood crime was unrelated to the participation in, or frequency of, LTPA. On the other hand, two neighborhood characteristics – distance to the nearest park ($\beta = -0.0262$, $p = 0.029$) and to the nearest non-residential destination ($\beta = -0.0735$, $p = 0.019$) – were associated with time spent on LTPA, but only among active older women. No neighborhood characteristic was related to participation in LTPA.

Conclusions: From a public health point of view, the provision of parks and non-residential destinations (shops, schools, cultural and worship places) might contribute to elevate PA levels of already active older women. On the other hand, in this setting, crime was not a big issue.

Keywords: Physical activity, Safety, Older adults, Parks, Destinations

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Background

Physical activity (PA) has numerous health benefits [1], but most people, and especially older adults, lead sedentary lifestyles [2]. Due to the increasing share of older populations in our societies [3], understanding the correlates of PA in this demographic group has never been so important. Physical activity habits are influenced by a myriad of aspects, including the social and physical environment [4]. The last two decades have been fertile in studies trying to determine the association between physical and social characteristics of the neighborhood and PA among older adults. But research on this topic is still not conclusive [5-7]. Literature shows mixed associations between different aspects of the neighborhood environment (access to parks/sport spaces or destinations, deprivation, land-uses, aesthetics) and PA [5-7].

Crime is one neighborhood characteristic that can act as a barrier to physical activity [8]. It is likely that people living in neighborhoods with high crime rates feel unsafe and, consequently, they might avoid engaging in PA in the neighborhood. Despite being a scientifically sound theory, neighborhood crime is one of the environmental correlates of PA that has led to more inconsistent and counterintuitive findings [9]. Perceived (self-reported) and objective (police recorded) measures of crime have been used in studies about this issue. The two provide distinct and complementary information [10], while objective crime expresses the likelihood of a crime occurring, perceived crime captures the individual interpretation of this tangible reality. Ideally, both perceived and objective crime should be addressed. Yet, studies using objective measures are particularly helpful because they are based on concrete indicators, making it easier to translate research findings into interventions that promote active lifestyles [11].

Older people have been subject to a limited number of studies relating crime and PA. In 2008, Foster and Giles-Corti reviewed all evidence about the topic and found that only 6 out of 41 studies have focused on samples of older adults [9]. Older adults are particularly vulnerable to the effects of neighborhood environments [12] and, principally older women, are more fearful of crime than any other demographic group [9,13-15]. Moreover, these studies have mostly used perceived measures of neighborhood crime [16-20] and as for adult samples, the results are not consistent – some detect significant associations [18-21] but others do not [16,17]. Further studies have since been published but the evidence remains limited: mixed results (6 studies detected some kind of association [10,22-26], but in 3 no association at all [27-30]); objective measures of crime were lacking [10,22,23,27]; and not all have dissected the effects of different categories of crime [10,23] (which might obscure the specific effect of some crime types).

Regardless of the neighborhood characteristics under analysis, Southern Europe has been neglected. Populations in Southern European countries rank among the oldest and most inactive in Europe [31,32]. Portugal, specifically, has one of the highest proportion of respondents saying they never exercise or play sport – 64 % of the adults (≥18 years) [31]. Populations residing in these areas therefore need further attention.

To address these gaps, we aimed to study the association between leisure-time physical activity (LTPA) among older adults and objective crime, without disregarding other neighborhood characteristics. Data will be drawn from a population-based cohort of adults residing in Porto (Portugal), and a wide range of objectively measured neighborhood characteristics will be used.

Methods

Setting

Located in the northwest of Continental Portugal, Porto municipality had approximately 240,000 inhabitants in 2008 [33], distributed across 41.7 km^2. Porto is limited by the Atlantic coast, and extends along the Douro River estuary. It is an industrial and port town situated in the Porto Metropolitan Area, the second largest metro area of Portugal with roughly 1.3 million inhabitants [34].

Participants

The EPIPorto Cohort encompasses a representative sample of 2485 adult (≥18 years old) inhabitants of Porto. Baseline evaluation was conducted from 1999–2003 [35]. Participants were recruited by random digit dialing using households as the sampling unit. After assessing the number and age of the residents of each household, randomization was applied to select one eligible person among the permanent adult residents.

The follow-up evaluation took place from 2005–2008. 1943 participants were contacted but 261 participants refused to participate, resulting in a response rate of 86.6 %.

The Ethics Committee of the Hospital de São João approved the study protocol. The study was carried out according to the Helsinki Declaration and all participants completed the informed written consent form.

Google Earth™ was used to georeference all addresses. For the present study, we included only adults aged 65 or more at the follow-up evaluation, i.e., 582 out of 1682 participants. Five participants were excluded because they moved outside of Porto.

Outcome: Leisure-time physical activity

Physical activity was evaluated using the EPIPorto Physical Activity Questionnaire to measure time and intensity of different types of activities, such as rest, transport to/from work, occupational, household and leisure [36]. A previous study assessed the validity, reproducibility and seasonal bias associated with past-year PA reporting, and it showed it is a valid and reproducible instrument for the brief assessment of different types of PA among adults.

In our study we focused on leisure time physical activities. In the EPIPorto Physical Activity Questionnaire, these included sedentary (playing cards, watching TV), light (e.g. brisk walking, golfing, snooker), moderate (e.g. walk at moderate pace, dancing, stretching) and vigorous (e.g. running, soccer, basketball) leisure activities. Because older adults benefit from PA even if light [37], we considered LTPA as the sum of the time (minutes/day) spent in non-sedentary leisure activities.

Two measures of LTPA were defined: time spent (minutes/day) in LTPA and participation in LTPA – inactive (0 min/day) and active (>0 min/day). We followed this approach because we theorized that the time active individuals spend in LTPA might be more influenced by neighborhood characteristics, whereas participation in LTPA might be more related to individual characteristics than to the neighborhood's [38].

Information about LTPA was available for 533 participants (out of 577), but one outlier observation had to be excluded, making a final sample of 532 participants.

Covariates: Individual variables

Individual characteristics were obtained through a structured questionnaire. We considered as confounders the following individual correlates of LTPA: age; marital status (married/non-marital union, single, widowed and separated/divorced); educational attainment (number of schooling years); retirement status (not retired/retired); smoking status (smoker, occasional smoker, non-smoker and ex-smoker); comorbidities (absence/presence of at least one of the following conditions – cardiovascular, respiratory, osteoarticular and musculoskeletal disorders, cancer, depression, cirrhosis and hypo/hyperthyroidism); residence in Porto for 20 years or more (yes/no); and body mass index (classified according to World Health Organization cut-offs).

Covariates: environmental variables

Neighborhood characteristics included as independent variables in the statistical analysis were: 1) socioeconomic status (SES) of the census tract of residence (three classes from the most to the least deprived [39]); 2) population density of the census tract of residence; 3) distance from the residence to the nearest park (24 parks); 4) distance to the nearest sport space (71 sport spaces); 5) distance to the nearest non-residential destination (includes churches, shops, libraries, museums and other points of interest) (421 non-residential destinations); 6) distance to the sea/riverside; 7) density of street intersections within 200 m of the residence (considered as the walkable distance for older individuals); 8) density of bus/metropolitan stops within 200 m; 9) average land gradient within 200 m. Since individual data refer to follow-up evaluation (2005–2008), all neighborhood characteristics were collected for a year within this time-window. The collection of the above mentioned variables and the georeferencing procedures were previously described [38].

The map of the participants' residence and neighborhood characteristics is displayed in Fig. 1.

Covariates: crime

Data about crime were obtained from the Public Security Police of the Metropolitan Command of Porto, which provided records of all crimes in Porto during 2008. The dataset included a description of the crime and the place of occurrence (street, neighborhood, street segment and, occasionally, exact position).

There were 17,790 records, from which 296 could not be georeferenced due to poor quality location information and 1776 were excluded because they corresponded to crimes (e.g. fraud, jobbery, copyright crimes) that were unlikely have an impact on the population's fear of crime and, consequently, PA.

Based on previous studies [10,23], we classified the remaining 15,718 crimes into the following categories: 1) incivilities (drug, vandalism, prostitution); 2) criminal offenses with violence, i.e., with approach to the victim (robbery, homicide, rape); 3) criminal offenses without violence, i.e., with no approach to the victim (theft, verbal offences) and 4) traffic (drunk/dangerous driving, speeding).

Further details about the georeferencing procedures and categorization of crime records can be found as additional material (additional file 1 and 2).

We calculated crime rates (/1000 inhabitants), by category, for each census tract; then a crime rate was attributed to each participant. Fig. 2 shows the spatial distribution of crimes rates across Porto municipality by category.

Statistical analysis

Descriptive statistics were computed for all variables, by sex and participation in LTPA (active vs. inactive). Mann–Whitney U and Chi-square tests were employed to compare distributions and proportions; the significance level was set at 0.05.

Generalized Additive Models (GAM) were used to estimate the association between LTPA and covariates. GAM extends generalized linear models to include non-parametric smoothing. This approach allowed us to model the spatial distribution of LTPA, and therefore to control for the presence of possible spatial autocorrelation.

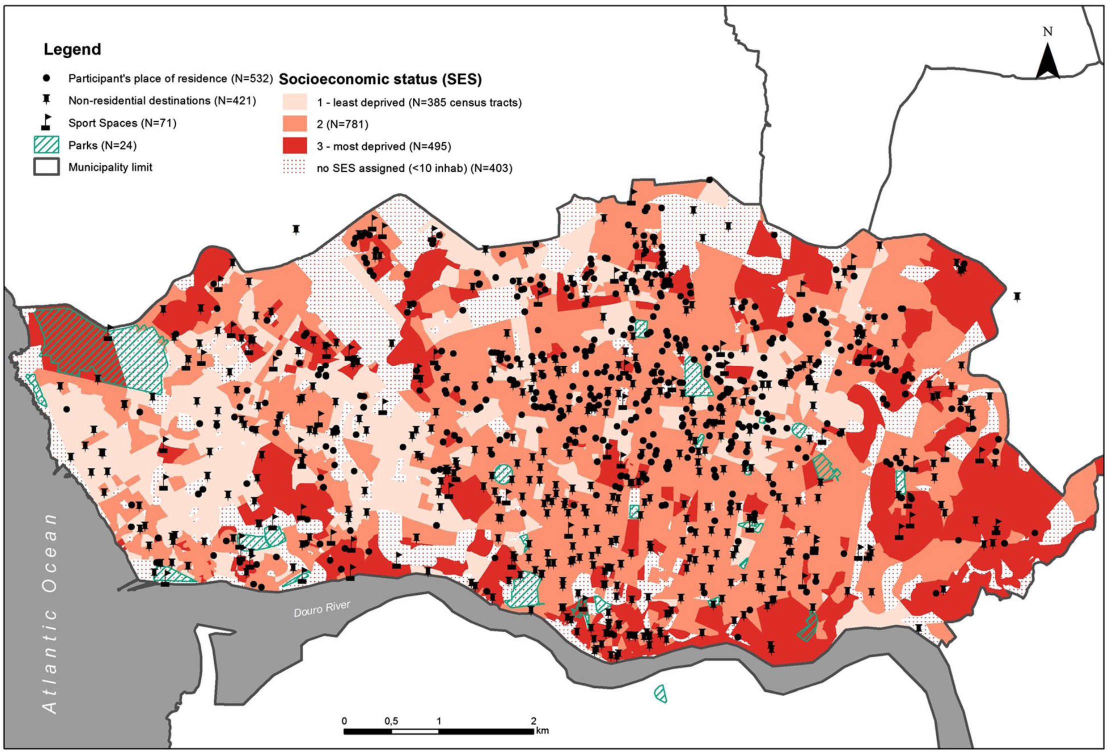

Fig. 1 Spatial distribution of the participants' residences and built and socio-environmental features (Porto, 2005–2008)

For data modeling, LTPA was used as a dependent variable and individual and neighborhood characteristics as covariates. Firstly, the association between spatial location of residence and LTPA was evaluated by applying a bivariate smoothing spline function on the pair of coordinates. Secondly, univariable analysis was conducted and all covariates with p-values ≤0.10 were included in the initial multivariable model. Then, each covariate was removed step by step until the final adjusted model was attained, eliminating consecutively those with the highest p-values. The final model included only covariates with p-values ≤0.05.

The presence of interactions was evaluated by including interaction terms between: 1) sex/marital status and area variables and 2) crime and other environmental variables.

Two models were fitted to test the hypotheses that 1) neighborhood characteristics were related to participation in LTPA and 2) neighborhood characteristics affect the time spent on LTPA among already-active persons. The first model, logistic regression, (eq 1) included the whole sample and assessed LTPA as a dichotomous variable (active/inactive). The second, linear regression, (eq 2) contained only active individuals, and assessed LTPA as a continuous variable (minutes/day). Given its skewed distribution, the variable LTPA (minutes/day) was log-transformed. The equations are presented below:

$$logit(y_i) = \beta_0 + \sum \beta_k x_{ik} + f(north_i, east_i) + e_i \qquad (1)$$

$$z_i = \beta_0 + \sum \beta_k x_{ik} + f(north_i, east_i) + e_i \qquad (2)$$

where y_i and z_i are the response variables, $\beta's$ are the coefficients of the model, x_{ik} are the explanatory variables, $f(north_i, east_i)$ is a smooth function of the coordinates and e_i are the residuals.

Due to the presence of interactions between sex and some neighborhood characteristics, sex-stratified models were built.

Results

Sample characteristics

The characteristics of the participants are shown in Tables 1 and 2. The sample consisted of 39 % men, and the mean age was 72.7 (5.6 SD, standard deviation) and 73.7 (5.9 SD) years old, among men and women, respectively.

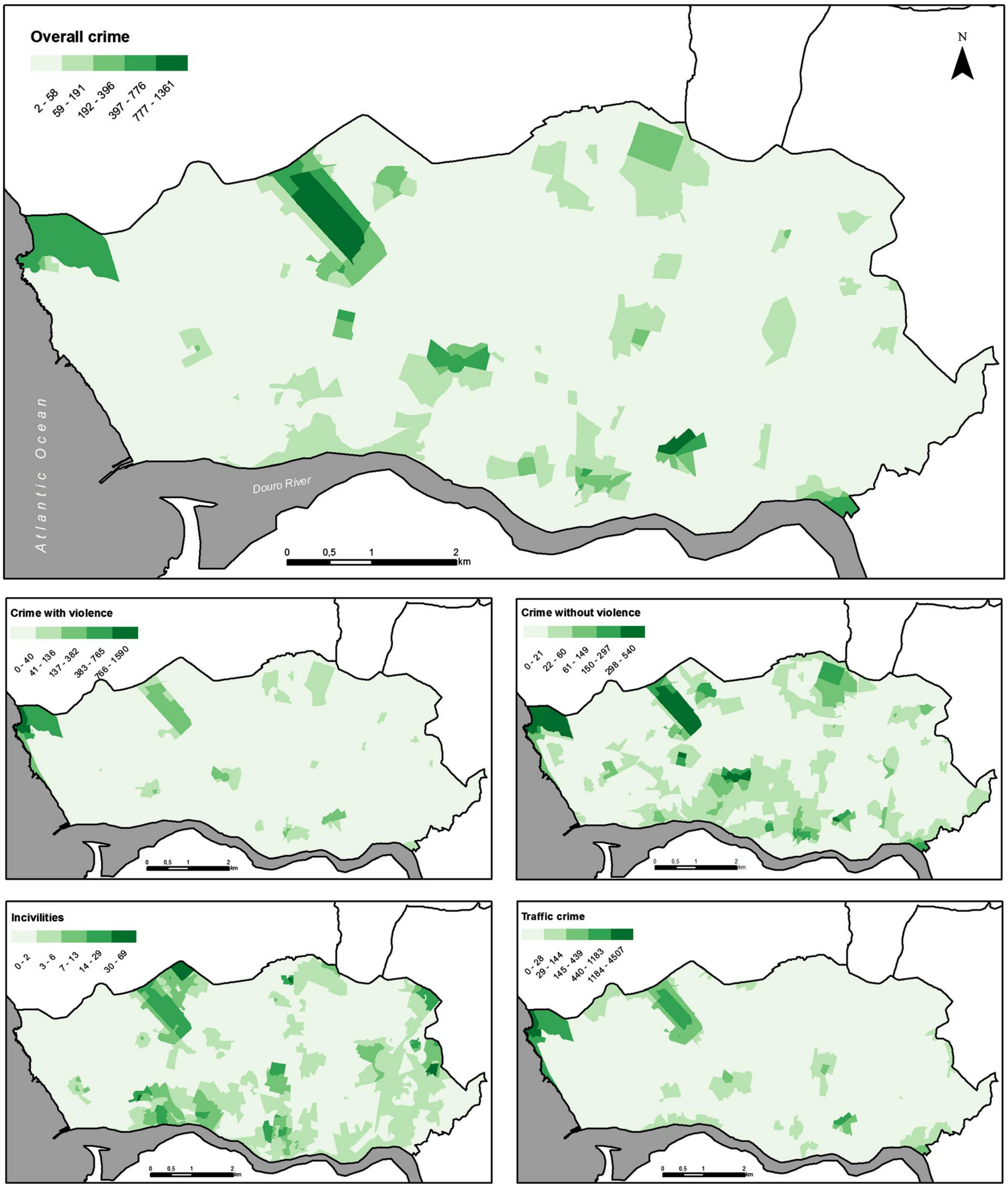

Fig. 2 Spatial distribution of recorded crime (Porto, 2008). *Spatial distribution of the crime rates (crimes/1000 inhabitants) by category*

Forty-six percent of the men and 61 % of the women do not engage any kind of LTPA. Among the active participants, men spend on average 50.5 (35.2 SD) min/day in LTPA, whereas women's average is 36.9 (35.1 SD) min/day ($p < 0.001$).

Men and women differ significantly in several aspects. Compared with women, among men we observed higher educational attainment, a lower proportion of chronically ill, obese and widowed, and a higher proportion of smokers.

Table 1 Characteristics of the participants (Porto, 2005–2008) according to participation in LTPA (inactive or active)

	Total ($n = 532$)		Inactive ($n = 294$)		Active ($n = 238$)	
	Women ($n = 323$)	Men ($n = 209$)	Women ($n = 198$)	Men ($n = 96$)	Women ($n = 125$)	Men ($n = 113$)
	Mean (SD[a]) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)
Age (yrs)	72.7 (5.6)	73.7 (5.8)	73.3 (6.0)	74.0 (5.7)	71.8 (4.7)	73.4 (6.0)
Marital Status*:						
Married/un-married union	142 (44.0)	182 (87.1)	92 (46.5)	82 (85.4)	50 (40.0)	100 (88.5)
Single	24 (7.4)	1 (0.5)	15 (7.6)	1 (1.0)	9 (7.2)	0 (0.0)
Widowed	140 (43.3)	23 (11.0)	82 (41.4)	12 (12.5)	58 (46.4)	11 (9.7)
Divorced/separated	17 (5.3)	3 (1.4)	9 (4.5)	1 (1.0)	8 (6.4)	2 (1.8)
Education attainment (no. years)***	5.5 (4.1)	7.3 (4.4)	4.8 (3.7)	6.6 (4.0)	6.6 (4.4)	7.9 (4.5)
Retirement status*:						
Not retired	62 (19.2)	8 (3.8)	39 (19.7)	4 (4.2)	23 (18.4)	4 (3.5)
Retired	261 (80.8)	201 (96.2)	159 (80.3)	92 (95.8)	102 (81.6)	109 (96.5)
Residence in Porto (<20 years)	7 (2.2)	4 (1.9)	6 (3.0)	2 (2.1)	1 (0.8)	2 (1.8)
Comorbidities*:						
No	73 (22.7)	69 (33.0)	45 (22.8)	36 (37.5)	28 (22.4)	33 (29.2)
Yes	249 (77.3)	140 (67.0)	152 (77.2)	60 (62.5)	97 (77.6)	80 (70.8)
Body Mass Index***:						
Underweight (<18.5)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Normal (18.5-24.9)	69 (21.6)	70 (34.1)	39 (20.0)	23 (25.0)	30 (24.0)	47 (41.6)
Overweight (25.0-29.9)	136 (42.5)	102 (49.8)	77 (39.5)	51 (55.4)	59 (47.2)	51 (45.1)
Obese (≥30.0)	115 (35.9)	33 (16.1)	79 (40.5)	18 (19.6)	36 (28.8)	15 (13.3)
Smoking habits***:						
Smoker	6 (1.9)	19 (9.1)	5 (2.6)	5 (5.2)	1 (0.8)	14 (12.4)
Occasional smoker	1 (0.3)	2 (1.0)	1 (0.5)	1 (1.0)	0 (0.0)	1 (0.9)
Non-smoker	290 (90.3)	72 (34.4)	182 (92.9)	31 (32.3)	108 (86.4)	41 (36.3)
Ex-smoker	24 (7.5)	116 (55.5)	8 (4.1)	59 (61.5)	16 (12.8)	57 (50.4)
LTPA[b] (minutes/day)***	14.3 (28.2)	27.3 (36.1)	0.0 (0.0)	0.0 (0.0)	36.9 (35.1)	50.5 (35.2)

*$p \leq 0.05$ comparing men and women
**$p \leq 0.05$ comparing active and inactive
[a] *SD* standard deviation
[b] *LTPA* leisure-time physical activity

Active participants were more educated and less likely to be obese than inactive individuals.

Regarding the neighborhood characteristics, on average, participants had parks, sport spaces and non-residential destinations within a distance shorter than 1000 m from their residence. The average street intersection density was 12 nodes/ha, and participants had on average 3 bus stops in a radius of 200 m around their residence. Most of the participants (61 %) were classified as medium SES neighborhoods.

The majority of the crimes (57 %) corresponded to criminal offenses without violence (*circa* 22 occurrences/1000 inhabitants) and the reporting of incivilities was rare (*circa* 0.4/1000). After non-violent crime, traffic crime was the most common crime category (*circa* 7/1000), followed by criminal offenses with violence (*circa* 6/1000).

Active and inactive participants did not differ in most neighborhood characteristics, except in relation to socio-economic deprivation and land gradient, which seemed lower among active participants. Men and women did not differ in any of the neighborhood characteristics.

Role of neighborhood environment on LTPA

We observed no spatial autocorrelation in the distribution of LTPA (either active/inactive or min/day). Consequently, the spatial smoothing term was excluded from the models.

Table 2 Characteristics of the participants' neighborhood environment (Porto, 2005–2008) according to participation in LTPA (inactive or active)

	Total (*n* = 532)		Inactive (*n* = 294)		Active (*n* = 238)	
	Women (*n* = 323)	Men (*n* = 209)	Women (*n* = 198)	Men (*n* = 96)	Women (*n* = 125)	Men (*n* = 113)
	Mean (SD[a]) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)	Mean (SD) or No. (%)
Distance to the nearest parks (hm)	9.9 (6.4)	10.9 (6.6)	9.7 (6.2)	10.9 (7.1)	10.3 (6.6)	10.8 (6.2)
Distance to the nearest sport space (hm)	10.0 (4.7)	6.6 (3.5)	9.7 (4.7)	6.6 (3.4)	10.4 (4.7)	6.7 (3.5)
Distance to the nearest non-residential destination (hm)	3.3 (2.2)	3.5 (2.3)	3.3 (2.1)	3.4 (2.3)	3.3 (2.5)	3.5 (2.3)
Distance to the sea/riverside (hm)	33.9 (11.0)	32.6 (11.5)	34.7 (11.4)	33.0 (11.4)	32.7 (10.5)	32.3 (11.7)
Intersection density[b] (nodes/ha)	12.3 (6.7)	12.5 (6.8)	12.7 (6.9)	12.2 (6.4)	11.6 (6.3)	12.7 (7.2)
Bus/metropolitan stops (no.)[b]	3.4 (1.9)	3.2 (1.9)	3.5 (1.9)	3.3 (2.1)	3.2 (1.8)	3.2 (1.7)
Land gradient (%)[b]#	5.0 (3.6)	4.8 (3.2)	5.1 (3.5)	4.9 (3.1)	4.7 (3.7)	4.8 (3.3)
Population density (inhab./km2)[b]	13549.1 (9208.9)	13270.3 (9071.5)	13795.7 (9869.8)	13976.6 (10415.9)	13158.6 (8075.0)	12670.3 (7746.7)
Neighborhood SES[c]*:						
1 – least deprived	66 (20.4)	48 (23.0)	37 (18.7)	16 (16.7)	29 (23.2)	32 (28.3)
2 – medium deprived	202 (62.5)	123 (58.9)	122 (61.6)	58 (60.4)	80 (64.0)	65 (57.5)
3 – most deprived	55 (17.0)	38 (18.2)	39 (19.7)	22 (22.9)	16 (12.8)	16 (14.2)
Neighborhood crime (crimes/1000 inhab.):						
Incivilities	0.4 (0.8)	0.4 (0.5)	0.5 (1.0)	0.4 (0.4)	0.4 (0.5)	0.4b(0.6)
Crime without violence	22.4 (20.4)	20.9 (21.2)	20.3 (16.6)	21.8 (23.3)	25.7 (25.0)	20.1 (19.4)
Crime with violence	5.9 (7.5)	6.0 (8.3)	6.7 (8.6)	6.1 (10.0)	4.7 (5.1)	5.8 (6.5)
Traffic crime	7.5 (17.2)	7.1 (13.2)	7.7 (19.1)	6.2 (10.7)	7.3 (13.7)	7.8 (14.9)
Overall crime	26.9 (34.0)	25.9 (26.7)	29.6 (40.3)	24.7 (26.6)	22.7 (19.7)	26.9 (26.9)

*$p \leq 0.05$ comparing active and inactive
[a]*SD* standard deviation
[b]Within 200 m circular buffer
[c]*SES* neighborhood socioeconomic status

When considering the whole sample and the response variable as participation in LTPA (active vs. inactive), logistic regression models revealed no association between crime (and any other neighborhood characteristics) and participation in LTPA among men. We only found a significant association between participation in LTPA and the rates of non-violent crime (Odds Ratio, OR = 1.019; IC95% = 1.004–1.027, $p = 0.014$) among women.

Concerning the outcome as time spent in LTPA by active individuals, the results (Table 3) show the adjusted and unadjusted coefficients for the association between neighborhood characteristics and time spent by active individuals in LTPA. There was no significant association between crime and time spent in LTPA, regardless of the category. We also tested for interactions and found no significant association.

However, significant associations with other neighborhood characteristics were observed. In the univariable analysis, among women, distances to the nearest park and to non-residential destination were negatively associated with the time spent in LTPA. After adjustment, associations between the distance to the nearest park ($\beta = -0.0262$, $p = 0.029$) and non-residential destination ($\beta = -0.0735$, $p = 0.019$) remained. That is, for every 100 m increase in the distance to the nearest park and non-residential destination, the time spent in LTPA reduces $((1 - e^{\beta}) \times 100)$ by 2.6 % and 7.1 %, respectively.

In men, we observed a positive association between distance to nearest sport space and LTPA ($\beta = 0.0462$, $p = 0.032$).

The proportion of the explained variability in LTPA (minutes/day) of the linear models was 17.1 % for women and 10.9 % for men; higher than in the logistic model (active/inactive), where it did not surpass 10 % for women and 7 % for men.

Discussion

Our study represents one of the most comprehensive studies of neighborhood influences on physical activity among older adults from southern Europe, and the first addressing the impact of neighborhood crime. We found neighborhood crime was unrelated to the practice or the

Table 3 Association between time spent in leisure-time physical activity of active participants and neighborhood characteristics. Association between daily minutes spent in leisure-time physical activity (log-transformed) of active participants and neighborhood characteristics, stratified by sex (Porto, 2005–2008)

	Model 1[a]				Model 2[b]			
	Women		Men		Women		Men	
	Coefficient	*p-value*	Coefficient	*p-value*	Coefficient	*p-value*	Coefficient	*p-value*
Distance to the nearest park (hm)	−0.0275	0.017	−0.0063	0.573	−0.0262	0.029		
Distance to the nearest sport space (hm)	−0.0297	0.068	0.0471	0.017			0.0462	0.032
Distance to the nearest non-residential destination (hm)	−0.0750	0.014	0.0125	0.680	−0.0735	0.019		
Distance to the sea/riverside (hm)	−0.0031	0.669	−0.0011	0.852				
Intersection density[c] (nodes/ha)	−0.0073	0.549	−0.0070	0.471				
Bus/metropolitan stops (no.)[c]	0.0093	0.828	0.0089	0.823				
Land gradient (%)[c]	−0.0254	0.221	−0.0102	0.628				
Population density (inhab./ha)[c]	0.0006	0.495	−0.0005	0.596				
Neighborhood SES[d]								
1 – least deprived	Ref		Ref					
2 – medium deprived	−0.0394	0.832	0.0242	0.879				
3 – most deprived	−0.1358	0.612	0.1921	0.393				
Neighborhood crime (crimes/1000 inhab.)								
Incivilities	−0.0008	0.996	−0.0008	0.995				
Crime without violence	−0.0015	0.615	0.0029	0.423				
Crime with violence	−0.0081	0.593	0.0012	0.991				
Traffic crime	0.0045	0.422	0.0020	0.669				
Overall crime	−0.0156	0.689	0.00038	0.883				

[a]Univariable regression
[b]Multivariable regression adjusted for age, educational attainment, marital status, retirement status, residence in Porto for 20 years or more, comorbidities, BMI and smoking habits
[c]Within 200 m circular buffer
[d]*SES* neighborhood socioeconomic status

frequency of LTPA. On the other hand, we observed that other neighborhood characteristics – distance to the nearest park and to the nearest non-residential destination – were associated with the time spent on LTPA, but only among older women that were active in some way. These characteristics were also unrelated to whether they were physically active or not.

Regarding the role of our primary neighborhood variable, objective crime, results did not corroborate our hypothesis. No main or interaction effects between neighborhood crime (and its categories) and PA were found. We only found a positive association between participation in LTPA and non-violent crimes among women.

Several studies have reported that crime, dissuades seniors from being active [10,18-23,25,26,40]. The fewer studies using objective measures of crime [10,21-23] actually provide evidence for such an association, whereas within the group of studies based on measures of perceived crime [16-20,25-30,40], null associations were frequent [16,17,27-30]. The fact we could not identify significant associations between PA and neighborhood crime might result from three possible explanations: (i) low risk of crime; (ii) walkable neighborhoods are attractive to crime; and (iii) social/cultural factors alleviate feeling unsafe.

Porto, like most Portuguese cities, is a relatively safe urban area and the few existing threats might not suffice to dissuade older adults from engaging PA. Portugal is at the bottom half in the rank of the European Crime Statistics, having lower crime rates than the UK, France or Spain [41]. The studies we found about the role of objective crime on older adults PA were undertaken in different countries and/or cities (USA, Oslo and Amsterdam), where crime might be a bigger issue.

Another plausible explanation lies with the fact that the same areas which provide destinations to walk do also provide opportunities for crime. The resources that define a walkable neighborhood – presence of shops, recreational facilities, dense transportation network, street connectivity, and food and alcohol outlets – have been associated with higher levels of crime [42-45]. Therefore, the negative influence that crime exerts on PA might be silenced by the positive impact of living in a walkable neighborhood. A recent study demonstrated that this seems to be a very plausible explanation of the null or counterintuitive findings found in studies about the effects of neighborhood crime on PA [46]. Notice that we found a positive association between neighborhood crime and PA in women, which happens to be the same demographic group whose PA levels increased with the proximity to non-residential destinations (shopping centers, recreational places). In our study we sought evidence for interactions between crime and other characteristics but we were not able to detect any, not even between neighborhood crime and distance to non-residential destinations.

Finally, another possible reason of the null associations might derivate from the specificity of the Portuguese social context. Social interactions and strong family ties in Portugal, and other Southern European countries, tend to be more common than in northern countries (where most studies have been performed) [47-49]. Studies have shown that perceived safety and self-efficacy might be determined by social support within the family and community [50,51].

In our study we also found no evidence that neighborhood characteristics significantly influence whether older adults are physically active or not. That represents no novelty for us. In a previous study, using baseline data (1999–2003) from the same population-based cohort, we found that neighborhood characteristics did not define whether older adults were active (some PA) or inactive (no PA at all). As in the present study, access to parks and non-residential destinations was only relevant among the elderly who already participate in PA [38]. Very few studies have looked at LTPA this way (both as dichotomous and continuous variables) but two processes are involved here and should be analyzed separately: participation in any LTPA at all and the amount of time dedicated to LTPA. Physical activity (and other health-related behaviors) is chiefly shaped at early life-stages and depends upon personal characteristics (e.g., sociocultural and educational aspects, or even physician recommendation) [52,53]. Thus, it would be unlikely that neighborhood environments effect an older person who has never exercised in his/her entire life. On the contrary, for those that already exercise on a daily basis, having an extra exercise facility in their neighborhood might increase their levels.

On the other hand, the associations we found between LTPA and proximity to parks and non-residential destinations corroborate the literature on the topic. The role of parks in PA has been extensively studied and it seems that access to parks may encourage people to engage in PA by, for example, providing increased opportunities for walking and cycling [20,54-56]. Similarly, access to non-residential destinations (sometimes expressed as land-use mix) has been consistently associated with increased PA among the elderly [25,28,56-59].

In our study, these associations were exclusive to women. The explanatory capability of our models, although modest, was higher in women (17 %) than in men (11 %), implying neighborhood characteristics have lesser impact on men's choices and attitudes toward PA. Accumulated knowledge on this topic suggests that residential environments might be more important for women's health and health-related behaviors than for men's [60].

In men, we found a positive association between distance to the nearest sport space and time spent in LTPA – those living farther away spending more time. A possible explanation for that unexpected finding would be the presence of unaccounted characteristics near sport spaces that dissuade PA (such as noise, pollution, social capital). As previously stated, we believe that among men, individual motivation and social support (e.g. having friends around to play with) might be much more relevant in shaping their PA habits than neighborhood characteristics.

Limitations

Our study has some limitations to consider. First, the cross-sectional nature of the study does not allow us to prove causal associations, due to the possibility of reverse causation and unmeasured confounding. Secondly, although we included a wide range of neighborhood characteristics, we could not incorporate characteristics known to affect PA, such as traffic [58], aesthetics [61] and social support [25,61]. Due to data unavailability, the role of perceived neighborhood environment, namely perceived crime, could not be explored. Third, we relied on self-reported PA, which might lead to recall and reporting bias. However, the EPIPorto PA Questionnaire was based on a well-established questionnaire and the validation procedure showed that it is a valid and reproducible instrument for assessing PA among adults [36]. Fourth, our measure of neighborhood crime might present some limitations as well. Objective crime refers to a single year (2008) and, although the overall crime rates did not change significantly in the proximate years, we cannot exclude the hypothesis that small space-time fluctuations occurred. In that circumstance, the use of crime records from other years/periods could have produced different results. Moreover, we cannot rule out the possibility that the crime records' accuracy varied by neighborhood, which could lead to individuals' differential misclassification.

Strengths

Our study has several strengths too. It represents one of the most comprehensive studies of the neighborhood influences on physical activity among older adults from southern Europe, and the first addressing the impact of neighborhood crime. The effects of neighborhood environments on PA might be context- and culture-specific. Consistency is one of the key criteria for causation: consistent findings observed by different persons in different places with different samples strengthens the likelihood of an effect [62]. Moreover, as previously referred to, the lowest levels of physical activity are clustered in Southern Europe and current economic constraints can only contribute to exacerbate this position [31]. Studies like ours might lead to interventions in urban design, which will improve population PA levels without being too costly - an important aspect when economic resources are limited. Secondly, we used a vast range of objectively measured neighborhood characteristics, minimizing bias due to unaccounted confounding variables. Third, crime was divided into different categories allowing us to determine the impact of each. Finally, our study contributes to consolidate the knowledge on an important, and still unsolved, public health issue – what are the urban environment correlates of PA? We believe the answer to that real-world question will lead to significant changes in urban planning policies.

Conclusions

We found no association between objective crime and the participation, and frequency of, LTPA among older adults. On the other hand, two neighborhood characteristics – distance to non-residential destinations and parks – were related to the time spent in LTPA, but only among older women that were active in some way. We also found no evidence that neighborhood characteristics define physical activity habits – being active (some PA) or inactive.

From a public health point of view, the provision of non-residential destinations such as shops, cultural and worship places, schools and parks might contribute to elevate PA levels of already active seniors. Yet, a profound change of PA habits might require multifaceted strategies that include environmental modifications, but also individual guidance provided by physicians, educators and mass media.

Additional files

Additional file 1: Georeferencing of crime records.
Additional file 2: Categorization of crime records.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
AIR designed the study, performed the statistical analysis and drafted the manuscript. AP participated in data collection and helped to perform the statistical analysis. MSC contributed to the interpretation of results and helped to draft the manuscript. MFP designed the study, contributed to the interpretation of results and helped to draft the manuscript. All authors read and approved the final manuscript.

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6. Discussion

6.1. Chapter introduction

This chapter summarizes and discusses the main findings of this thesis, places the results in context with the existing literature, discusses the overarching strengths and limitations, and explores the implications of the current work for policy and future research.

6.2. Summary of the results

This thesis was focused on the spatial inequalities and determinants of old-age survival and active ageing. We started by providing a Europe-wide view of the magnitude of the inequalities, but we gradually augmented our scale of analysis, until we reach the neighbourhood level.

In Europe, important geographical cleavages in the distribution of old-age survival exist: in some areas less than 30% of the 75-84 years old population reached 85-94 years of age; in others the proportion of survivors went well beyond 50%. High old-age survival covered north-eastern Italy, but especially northern Spain, and France. Lower survival predominated in parts of the UK, Scandinavia and Netherlands, and in some areas of Southern Europe.

These results led us to investigate the causes of the observed spatial divide. Information on the possible determinants of old-age survival had to be gathered and transformed into multivariate indexes. Four evidence-based ecological indexes were then created. One of these indexes summarized the socioeconomic characteristics of the European areas, the European Deprivation Index (EDI), and was generated for five European countries at the neighbourhood level using both individual (survey-based) and ecological data (census-based) (paper II). The second summarized the physical environmental characteristics of the areas and it was created for Portuguese municipalities and Porto neighbourhoods, grounded on the methods used to develop analogous indexes in the UK and New Zealand (paper III). The third indicator focused on the access to healthcare especially for the eldest, and it was created for Portuguese municipalities, based on a wide range of indicators about human and material healthcare resources. The fourth indicator, the walkability index, aimed to characterize the urban built environment of Porto and was slightly adapted from previous studies conducted in the city.

The EDI was created for four other countries besides Portugal, which allowed us to conduct a cross-national study to understand the influence of socioeconomic deprivation on old-age survival (paper IV). Socioeconomic deprivation emerged as an important determinant. Most affluent areas registered 10-15% higher survivorship as compared to those in the lower end of the socioeconomic spectrum. We estimated that the elimination of these socioeconomic differences would increase old-age survival by 14%. But, it is important to note, there were substantial country-to-country differences in the magnitude of the effect of socioeconomic deprivation, being more pronounced in England, Spain and Italy, and lesser in Portugal and France. Overall, the association is steeper among women.

Therefore, we investigated which factors, besides socioeconomic determinants, could be implicated in the geographical inequalities of old-age survival. We hypothesized that physical environment and access to healthcare were involved in shaping these inequalities. Due to the absence of Europe-wide data on these factors, we focused on the Portuguese continental territory (paper

V). However, and contrary to our belief, we saw that socioeconomic deprivation was still the single most important determinant of old-age survival in Portugal. The contribution of healthcare aspects was smaller, and the impact of physical environmental quality was null.

A possibility remained that the limited role of previous factors was an artefact of the geographical unit of analysis we employed in the previous studies (the municipality). Thus, we decided to focus on the neighbourhoods of an urban setting where the socio-spatial segregation in health and consequently in older people survivorship could be more pronounced (paper VI). In this study, to aid local policy, we firstly determined critical areas of Porto in terms of old-age survival. In general, the worst areas located in the bottom centre (the old-town) and in the eastern part of the city, and the best ones concentrated in the western part of the city. Then, we explored the role of socioeconomic and physical environmental deprivation, biogeophysical (air pollution, climate, greenness) and built (walkability). As hypothesized, the effect of socioeconomic deprivation was starker in Porto than the one observed when we took Portugal as a whole. This effect was actually as strong (or even stronger) as the one observed in certain European countries. Most affluent neighbourhoods had a 30-50% higher survivorship as compared to the most disadvantaged. Physical environmental characteristics, again, played no role in explaining spatial inequalities in old-age survivorship.

It is argued that the socio-spatial patterning of health is the output of inequalities in the distribution of health related behaviours. There is compelling evidence that PA is a key determinant of survival later in life. At the ecological scale, no data about PA levels exists. Thus we used primary data from a population-based cohort to understand how PA of the older adults varied across neighbourhoods and to see in what extend it was also influenced by the physical, social and economic features of the residential environment.

Georeferencing is an unavoidable step to study the relations between individual outcomes and ecological variables. Conscious of the importance of this methodological step, we evaluated and critically described the main limitations and opportunities of each georeferencing tool (paper IX). It seems that, in absence of good street reference maps, the online open services are valuable alternatives. EPIPorto addresses were georeferenced based on that knowledge, which allowed us to then study the link between PA and neighbourhood environments (paper VII and VIII). A wide range of neighbourhood attributes were assessed using GIS: distance to resources (sport places and non-residential destinations), parks, river/sea, neighbourhood deprivation, land gradient, crime rates, street and transport network, and residential density.

But, in the end, we found that only two attributes of the neighbourhoods impacted significantly the frequency of leisure-time PA of our samples of older adults – distance to parks and distance to non-residential destinations. We did found however these two attributes play a limited role in influencing the practice of PA: they did not relate to whether or not older adults where active or inactive; they were just slightly associated with PA frequency among the somehow active participants. Gender differences were found as well, with our results pointing towards a larger effect of the neighbourhood characteristics among old females.

6.3. Discussion of the key findings

Spatial inequalities in survival exist in late life, keep almost unchanged through time, and the spatial patterns are very alike to those of premature mortality

Several studies have looked on the geographical patterns of key population health indicators, being them life expectancy, overall mortality, or CVD mortality. In our study we added old-age survival to that list, which we estimated by computing the proportion of people aged 75-84 old who ten years after were still alive. Despite our study have used considerably smaller units, we observed that the geographical divide of old-age survival was not very different from the geographical divide of premature and avoidable forms of mortality, such as CVD disease (79, 357), infant mortality (358), mortality below age 65 (358), or life expectancy at birth (62, 78, 79).

Such similarity reveals two things. First, spatial segregation in health is observed in all age stages and is not that small later in life contrasting to what was initially thought. Secondly, the geographies of premature mortality and late mortality match quite well, which indicates that the underlying causes of these differentials could coincide too.

About this consistence in mortality spatial patterns across the life-course not much has been published. But, in the 1980s, a reference study from Barker had compared the geographical distribution of ischemic heart disease and infant mortality in the UK, and identified an almost perfect matching between the two, coincidence that Barker attributed to poverty (359). Several studies have found that the geographical cleavages in mortality are time-persistent (360). That was observable in our Europe-wide study where we looked at old-age survival within two distinct periods 1991-2001 and 2001-2011 and concluded that worst-off and better-off risk areas stayed almost unchanged. Looking at a much longer time-series, and despite all medical, social and economic changes, in the UK, the modern patterns of mortality in 2001 remain closely related to the patterns of a century ago, in 1901 (361). In Italy, the North/South divide we observed in old-age survival exists for infant mortality too and has remained substantially unchanged since the 1960s (362). This temporal consistency in mortality geographical patterns can be found in German studies as well, where, despite the fall of the Berlin Wall, almost 30 years ago, mortality rates are still about 50% higher in the East compared with the West (363). The same is verified in the ex-communist countries, which even after their entrance in the EU, have worst health indicators than their western counterparts (21).

It is also interesting to note that, in our study, Portugal was an outlier country inserted in a generally favourable area, a spatial continuum constituted by France, Italy and Spain with the highest old-age survival rates of the 18 countries considered.

The outlier position of Portugal was highlighted by other authors in the past concerning its levels of life expectancy at birth in the 1960s (18). Supposedly, Portugal had recuperated and it is now at the level of other core EU-members (19). It might be truth for life expectancy at birth, but for old-age survival, which is now a much better indicator of human development, Portugal still maintains a somewhat disadvantaged position. Regarding another global indicator of health, healthy life years, the same is observed – Portugal is behind the core members of the EU (364, 365). Specifically, about the regional and local disparities in health in Portugal not much has been done, and no study was conducted within Porto municipality. Medical geography is still an embryonic discipline in our country. Still, Santana and colleagues have found geographical differences in rather specific mortality causes, such as diabetes (366) and suicide (367). Likewise our study these investigations placed Alentejo (at south) among the worst performing regions of the country, which was also observed by Ribeiro (368) and Almeida (369) regarding the risk of CVD mortality.

And why these spatial inequalities occur during the entire life-course and persist through time and across space? Although we cannot provide a definite answer to this question, we do believe it is mostly related to the persistence of the geographies of socioeconomic deprivation. As we will discuss, our study has found socioeconomic deprivation as the single most important contextual factor of old-age survival in Europe, Portugal, and Porto.

Regardless the area and scale of analysis, socioeconomic factors play a decisive role in shaping the geography of old-age survival.

In our study we found that the contextual factors that most affected older age survival were socioeconomic ones. The prominence of socioeconomic aspects has been observed in numerous studies. The USA County Ranking Study (370) concluded through extensive literature review the socioeconomic factors account for 47% of the differences in population health, followed by health behaviours (34%), clinical care (16%), and the physical environment (3%). The Canadian Senate published comparable results too (371). Accordingly, social and economic context is responsible for 50% of the health differences between Canadians, followed by healthcare (25%), by biological factors (15%) and, lastly, by environmental features (10%).

Although it was not our aim to reach these type of figures, our results allowed us to make a similar exercise. In the different studies we conducted using diverse scales of analysis and study areas we found that much of the spatial variability in old-age survival was explained by socioeconomic factors. The addition of aspects related to the healthcare contributed to explain a small share of that variability, but, after controlling for socioeconomic deprivation, our results were no longer statistically significant. This is probably due to the spatial coincidence between the patterns of socioeconomic deprivation and access to healthcare. Regarding the role of physical environment, we were able to verify (papers VII and VIII) it influenced PA behaviours among urbanites but not old-age survival (at least not directly).

The overarching and strong effect of socioeconomic deprivation on old-age survival merits further exploration of the potential mechanisms involved, which are certainly numerous and complex (108, 109):

- Material conditions might contribute to this gradient. According to the (neo)material theory, the SES of the individuals defines the material conditions to which they are exposed: low income communities lack essential resources and are subject of an underinvestment in diverse physical, health and social infrastructure. In our study we found access to healthcare to be lower among deprived areas, as compared to the most advantaged. The "inverse healthcare law", as Tudor labelled it, has been observed almost universally (372). Yet, and contrasting with what has been reported, we did not found – at least in Portugal - poorer areas to have poorer physical environments neither biogeophysical (air quality, climate, greenspace), nor built (access to destinations, recreation). Of course there were other environmental attributes we left unexplored, such as noise exposure, aesthetics and, rather important, housing conditions.
- Psychosocial reasons might be implicated too. The psychosocial theory defends that people from lower SES experience more stressful and negative life events, making them more vulnerable to risky behaviours and less resilient to disease. This mechanism might be particularly relevant within urban settings (373), where uprooted people from different origins and back-

grounds are gathered together. Nevertheless, our study did not address this issue.

- Health-related behaviours are likely to be involved as well. The cultural-behavioural theory emphasizes that the socio-cultural context (norms, support, networks) frames behavioural choices, such as lifestyles (smoking, PA, diet) and attitudes towards healthcare (the use of healthcare resources and services). Numerous studies have found that established risk factors are socially patterned (374). In our study on PA, the only behavioural determinant we addressed, we saw a certain degree of socioeconomic stratification. Men from lower SES (measured by education and area deprivation) tended to be more active than the most affluent, whereas the opposite happened for women. Remember our population target was older adults and, among this age cohort in Portugal, mainly as consequence of the right-wing dictatorship that ruled the country for almost 50 years, gender roles were clearly compartmentalized, which eventually perpetuates over the time. Women, especially the most disadvantaged, were responsible for a wide range of domestic chores having less time to dedicate to leisure and career (375). Only the most advantaged were permitted to participate in physical activities and other leisure activities. Men, on the other hand, worked outside the home and had more autonomy to engage in group leisure activities, such as sports and gaming. We conjecture that sport culture was more entrenched in most disadvantaged population groups, whereas the most affluent engage more often in sedentary activities (readings, writing, playing).

Socioeconomic factors impact old-age survival but with varying degrees depending on the country and gender.

Due to our Europe-wide approach and to the use of internationally comparable indicators of socioeconomic deprivation, we were able to explore the impact of deprivation in survival across distinct countries which, despite sharing a common epidemiological and demographic background, embody different cultures, history, and social and political traditions. These differences were mirrored in our results. The magnitude of the association between survival and socioeconomic factors was considerably larger in England, Italy and Spain than in France and Portugal. The existence of these country-specific associations has not straightforward explanation and most theories and conceptualizations fail in one or other aspect in explaining the observed cross-national differences.

The welfare regime theory partially supports the observed patterns. Recapping, the welfare regime refers to the state’s function in providing services, such as education and social protection (151). In Europe, despite different categorizations can be use, there are essentially four welfare regimes, here from the least to the most redistributive: Liberal/Anglo-Saxon (e.g. the UK), the Bismarkian/Conservative (e.g. France, Germany), the Southern European (e.g. Portugal, Spain, Italy), and the Scandinavian/Social Democratic (e.g. Sweden, Finland). More generous welfare regimes are thought to alleviate the impact of social conditions. Whilst this theory helps to explain the generally smaller impact of socioeconomic deprivation in Portugal and France and the starker differences in England, it does not provide any insight on the patterns observed in Spain and Italy. It is important to note, the welfare regime theory has been subject of numerous criticisms (376), and this classification, namely the inclusion of Portugal, Spain and Italy in the same group, might need to be revised, and the welfare regime may affect one dimension of socioeconomic inequalities in health (e.g. income), leaving others intact (377). The failure of this theory is patent in numerous studies that observed the magnitude of the inequalities in health is not lesser in Scandinavia, allegedly a more egalitarian society.

Social support relates to informal support networks, and contrasts with the welfare provision, which delivers formal and structured support. Although social support is assumed to be a universal resource, cultural differences exist. Social and family ties, religious and charity groups are stronger in Mediterranean countries than in Western Europe (135). This might explain the lesser socioeconomic differences in old-age survival in Portugal and the wider inequalities in England, but provides no insight about France, Italy or Spain.

Universal and free healthcare systems might also aid to ameliorate the effects of deprivation; healthcare system typologies are not necessarily tied to the type of welfare regime. In England, with a Liberal welfare regime, the health system is free and fully universal. The countries we considered all have almost free and universal health systems; thus, this theory provides no reasoning to our findings. Of course other aspects (other than free/universal access) affect healthcare use, namely the geographical coverage of the healthcare resources, which was also matter of study in this thesis.

The social stratification of health behaviours could also aid to explain these patterns. Behaviours, such as smoking, food intake, PA, are generally less socially patterned in Southern Europe, though it does not fully explain our results. According to this hypothesis England and France should had the same degree of socioeconomic inequality as they are in the same stage of tobacco epidemic, the most deathful health-related behaviour affecting oldest cohorts.

The different degree of socio-spatial segregation could also contribute to the cross-country differences in the effect of deprivation. Socio-spatial segregation refers to the extent to which similar societal groups (based on income, ethnicity) reside close to each other. Much research on the area has looked at the degree of ethnic segregation across European cities, not exactly what we have studied. According to these studies the UK has the highest levels of segregation followed by Belgium, Netherlands and France (378). Focused on the UK, several studies have been highlighting the strong socio-spatial segregation of the British population, with the most deprived working classes living at north and the more affluent classes in the south and London area (379, 380).

Geopolitical motives are certainly implicated in the observed differences. The UK, Italy and Spain, contrary to Portugal and France, have a strong geopolitical divide which dates back to the birth of these nations. In the UK, besides the coexistence of four nations (England, Scotland, Wales and Northern Ireland), the present north-south divide was settled in Victorian times, with the North guaranteeing the industrial production of the nation[7] , being subordinate of the South where commerce and finance defined the production pace (381, 382). In Italy, only in the 19th century the southern provinces, underdeveloped and successively ruled by different invaders, were unified with the northern provinces where a middle class had time to flourish (381). Spain, despite being unified under the same sovereign in the end of the 15th century, had two states (Castella and Aragon) coexisting de facto up to the 18th century. As a corollary, today different languages, peoples, and cultures persisted alongside in the state that is officially composed by several autonomous regions of different degrees of economic development, being the South generally poorer than the North.

On the other hand, Portuguese frontiers date back to the 13th century and, although the South, dominated by the Moors up to then, was initially less economically advanced, the north-south divide was attenuated when the capital city was moved to the South (from Coimbra to Lisbon). Contrasting with Spain, the Portuguese are a unique nation and even regional identities have always had a weak expression (383). Lastly, in France the expansion of the state started from a central core which remained unchanged, through the annexation of peripheral regions (e.g. Corse,

7 With the Thatcher governance these regions then suffered massive de-industrialization (Northern England, Scotland and Wales), resulting in high unemployment rates and in a fragmented society.

Alsace, Lorraine, Brittany, Roussillon), being the frontiers consolidated in the 18th century. As an output, although regionalisms and even separatisms are still present in today's France, since the French Revolution the French language and culture were imposed to all country, now one of the most centralized in Europe (384).

Finally, there is always possibility that our results are artefactual. Despite EDI being comparable between countries and variables being chosen based on the country experience of deprivation, the availability of variables at aggregated level was larger in the UK and France than in Portugal, Spain and Italy, so that those indexes might be "richer" and better grasp the concept of deprivation than those of Portugal, Spain and Italy. Geographical areas were also different in size, larger in France and England. But, considering that the use of large areas usually obscures inequalities, it would be expected the effect of socioeconomic deprivation to be lower in England.

We also found the associations between old-age survival and socioeconomic deprivation were stronger among women. Results on this topic are particularly inconsistent. There is substancial evidence showing women are particularly affected by socioeconomic circumstances and other contextual factors (385, 386), and our results corroborate these findings. However, several ecological studies about socioeconomic inequalities in mortality have found the exact opposite (387-389). From our perspective, it is actually plausible that inequalities among women become wider later in life. Due to a delayed health selection the pool of women that reaches advanced ages it is expected to be more diverse in terms of socioeconomic characteristics.

Urban settings are unequal places and hold large health disparities

Our study confirmed our initial suspicious and what has been said in the literature, urban settings hold quite large health inequalities (390). In Porto, a 4x9 km rectangle, we identified areas with survival rates lesser than 30%, whereas others enjoyed survivals as high as 70%. The wide geographical gap in Porto might have numerous explanations. The high degree of socio-spatial residential segregation seems to be the most plausible explanation.

The segregation of residential areas in Porto dates back from late 19th century, when industrialization and massive rural exodus happened (391). By then, the core medieval borough (now called historical centre), composed by the parishes of Sé, São Nicolau, Vitória, Santo Ildefonso and Miragaia, exhibited extremely high population density, with serious problems of overcrowding, insalubrity and infectious epidemics (essentially tuberculosis and plague). At the same time, a very specific type of housing for working class burgeoned in the city particularly in the industrial parishes (Bonfim, Santo Ildefonso, Cedofeita, Massarelos and Lordelo). The type of housing called "ilhas" ("islands"), which is still part of Porto urban tissue, grew in the backyards of the middle class houses and offered no hygiene conditions to the occupants (392). The rich and elegant neighbourhoods of Boavista, Álvares Cabral and Duque de Bragança, situated in recently opened avenues, were also constructed that time. And, the most emblematic example of residential segregation in Porto is also a 19th century creation – the "Bairro dos Ingleses" ("The Englishmen Neighbourhood") located in the Douro estuary in the "Foz" area of exclusive residence of a colony of Porto wine traders.

Interestingly, these contrasts subsisted to our time and the distribution of the old-age survival follows this socio-spatial division of the city (Figure 10). In the 20th century new housing was constructed in the peripheral parishes to tackle overcrowding, health and social problems of the city core, budgetary ceilings where in accordance to the geographic location and social composition of the residents. Date this type the construction of Gomes da Costa and Costa Cabral neighbourhoods located in Foz and Antas, and the public housing complexes of Azenha and Ilhéu, located in more disadvantaged areas in Paranhos and Campanhã.

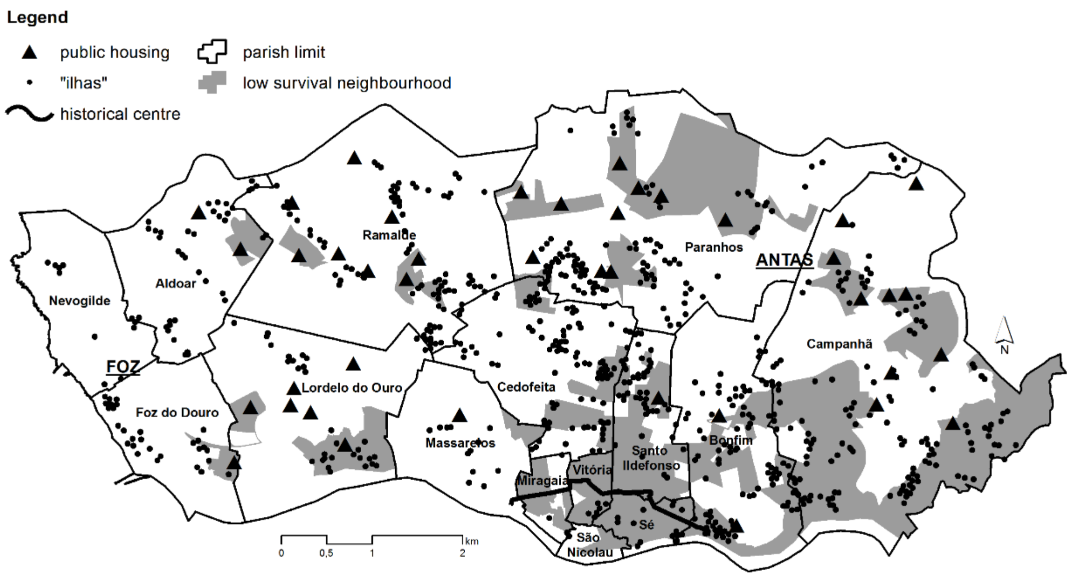

Figure 10. Location of the historical centre, public housing complexes and "ilhas" across Porto municipality and location of the places of high and low old-age survival.

The high degree of segregation in the city is mirrored in the relative risks for survival we estimated: 1.3 to 1.5 within Porto least deprived neighbourhoods, whereas when taking the country as a whole those risks where less than 1.1 and often statistically non-significant. Still, it is important to note that the "ilhas", one of the poorest forms of construction in the city, are encrusted even in the most affluent neighbourhoods, which means that our study areas, despite being small, might still conceal important inequalities in health. In the Lisbon Metropolitan Area, despite these studies were anchored in larger geographical units and in other outcomes, Santana et al and other researchers also found higher mortality risk in the most deprived areas of the city. However, relative risks of mortality in most disadvantaged neighbourhoods were comparatively smaller than ours: generally lower than 1.2 and some statistically non-significant (203, 387, 388). The motives for the contrasting results obtained in Lisbon and Porto should be sought.

Another reason for such high degree of spatial inequality in old-age survival in Porto might also derive from the geographical scale that was used. Porto was divided into much smaller units than Portugal and Europe. Usually the larger the areas used in a certain analysis the lesser the difference between them. If in England unitary authorities might be large enough to capture population inequalities in health, in Portugal, due to the lesser socio-spatial segregation of the territory, municipalities might prohibit us to see differences between populations. Smaller units, like the neighbourhoods, tend to better represent the residential environment, the characteristics, exposures, and problems of a certain population. Assessing health inequalities at different scales of analysis is crucial because the absence of relevant differences in one level of analysis does not necessarily mean they do not exist.

Urban built environments affected older adults' physical activity levels but associations were modest and gender-specific

Physical activity is associated with numerous health benefits and since the 2000s studies started to evaluate whether certain neighbourhood characteristics, physical and social, could impact PA levels of the population. Our study contributes to engross the evidence that says this relation exists. We found that two neighbourhood attributes were related to the time spent in PA among older adults – parks and non-residential destinations. Parks provide opportunities for people engage in PA, and are sought not only for exercise purposes but also for socialization. It is important however to refer that in the two studies where we assessed the role of neighbourhood attributes and PA results were not consistent. In the study using EPIPorto baseline information (1999-2003) we found an almost non-significant negative association between distance to parks and leisure-time PA frequency among older males. Among women no significant relation was observed, although univariable analyses revealed a slight negative relation too. Using data from the same cohort, six years later (2005-2008), the pattern inverted: among men no relation was observed but among women a negative association was found between distance to parks and time spent in PA during the leisure. Cohort effects might influence the attitudes of women towards the use of parks. Gender geography studies have showed that park use was more common among males, whereas women prefer utilitarian places (285, 393). But, do six years suffice to explain such societal change? Another possible explanation has to do with the fact that our study did not contemplated park characteristics. Quality of public spaces is certainly as important as distance (290) and these mixed-findings might reflect changes in park quality around these older adults.

Regarding the role of non-residential destinations, places that older adults visit for utilitarian, social and recreational purposes, our results corroborate the existent literature on the topic, that says having community resources in the neighbourhood is associated with increase PA among the eldest (and also among younger age groups). Yet, this result was exclusively found among women. Older women, especially in Mediterranean traditional societies, are the ones responsible for house chores, grandchildren care, shopping, so that the presence of non-residential destinations in the neighbourhood might enhance walking behaviours among older women. The presence of gender differences have been highlighted by the studies addressing neighbourhood effects – women and men perceived and valorise environmental features differently (386). For instance, the presence of neighbourhood problems, such as crime and disorder, has been more consistently associated with women PA than with males. Aware of the importance of safety among the older population, particularly among women, we tested whether the presence of crime in the neighbourhood – covering different categories from the more mild forms to the most violent – were associated with senior PA levels. In this study, however, we have not confirmed this supposition and we did not found older adults that resided in neighbourhoods with highest crime rates to be less physically active.

Our studies on the link between PA and urban features also permitted us to verify that, despite all the hype around the social-ecological way of thinking, neighbourhood characteristics have a limited impact on PA levels of the Portuguese older adults. We observed these characteristics only affected the frequency of leisure-time PA among the half of participants that was somehow active; when we considered the entire sample and looked at the impact of this same set of variables on whether or not they engage in PA, no relation was observed. And, only 2 out of 11 neighbourhood attributes influenced time spend in leisure PA.

6.4. Strengths and limitations

A key strength of this study was the use of high quality and comparable data about outcomes and determinants. To measure old-age survival in Europe we had to harmonize demographic data, but more importantly geographies. The shape of the administrative divisions changes at every census operation, especially the boundaries of the smallest areas. In this thesis, we aggregated areas and used geographies from the past to track populations through time, which required GIS-procedures but also an extensive review of the history of the European administrative divisions.

The EDI was grounded on the European Union-Statistics on Income and Living Conditions, EU-SILC, a longitudinal and Europe-wide questionnaire specifically designed to measure deprivation and its domains. Census data necessary to create a measure deprivation at ecological level was also harmonized between countries. The physical environmental deprivation index was also developed using Europe-wide datasets, namely those on air pollution, industrial sites and land-uses, which are frequently updated. The remaining variables were also provided by official institutions and, as the previous, are collected and updated with regularity. The use of regularly-updated high-quality data represents an important advantage of our work, and guarantees these indicators continue to be updated. The use of census data can also be seen as an important plus of our study. Population and housing census data in Europe have very high quality: generally universal and covering nearly 100% of the population. And, in countries which abandoned the full coverage census, the combination of population registries and sampling census guarantees similar accuracy.

Our study on the relation between PA and neighbourhood context relied on primary data of high quality standards. EPIPorto cohort started in 1999 and the last evaluation ended in 2014, a 15-year existence. In all evaluations similar methods and instruments were used, all applied by trained professionals. Also important to mention, the participation rate of this cohort is rather high, and the losses to follow up relatively small. Although objective measures of PA are usually preferred, the PA questionnaire from which we retrieved information on the PA levels of the older adults was shown to have good psychometric proprieties (394).

In our study we were particular attentive to the limitations of the georeferencing tools and we conducted a methodological research to ascertain which address georeferencing tool would yield the best results in terms of positional error and participant's misclassification risk. Based on that knowledge, EPIPorto participants, firstly georeferenced using a GIS and a street map provided by the city hall, were georeferenced once again using a more accurate tool, Google Earth. Consequently, the point position of the addresses used in papers VII and VIII do not fully match. Aware of that, we also investigated in what extent regression coefficients and conclusions would be different if using on method or the other. We then concluded that main results remained unchanged, suggesting positional errors were relatively small and non-differential at least in what concerns phenomena like those studied in the present thesis.

Another particular strength of the thesis is related to the chosen analytical methods. We have used methods that control for most limitations of the ecological studies – autocorrelation, excessive variance, and residual confounding. The Besag, York and Mollié (BYM) model (395) account for these problems by smoothing survival-rates and removing excessive values typical of areas with small population sizes, a big problem when dealing with restricted population groups, as the eldest. Moreover, when estimating the link between old-age survival and socioeconomic, physical environmental and healthcare conditions, the effect of unmeasured confounding variables was accounted as well. The BYM model includes two random effects, spatially structured and spatially unstructured, the former accounting the spatial structure of the observations, and the later dealing with the non-spatial variability. These effects act as latent confounding variables we were not able to account for. To identify those areas with extremely high/low survival we also relied on appropriate statistical methods (excursion sets), which guarantee truthful results. Within Porto, to determine the relation between neighbourhood attributes and older adults' PA levels, we also looked for the presence of spatial autocorrelation in PA. Generalized Additive Models allow us to control for eventual spatial autocorrelation in the observations and consequently to avoid inflating association measures (396).

Although the goal of the research was achieved, there are still limitations and constraints that might have affected the current analyses. These issues should be addressed in future research. Firstly, we could not validate our surrogate measure of survival. Data on mortality after 85 years old is generally not disclosed, life tables are also absent for small units of analysis, and even if available estimating old-age life expectancy after a certain age and at small areas is prone to bias (336, 337). We trust our indicator is reliable because the distribution of the estimates of old-age life expectancy and mortality at regional level, patent in other studies and reports, resembles ours. We were also able to pinpoint localities and defined regions previously referred as having high longevity (e.g. Emilia-Romagna, Italy) and low longevity (e.g. the UK and France post-industrial sites), which reinforces our methodology. Second, we are unable to assess whether these extra years of survival are accompanied by an extension of the healthy years of life. Notice that, extending healthy life years is currently a top public health priority (397). Third, we could not include eastern European countries and even other important Western European states like Germany, whose inclusion would enrich our analysis and conclusions. Fourth, because all the studies used some kind of ecological variable, our results can also be affected by the Modifiable Areal Unit Problem (MAUP), i.e., a different arrangement of our measures could have yield different results (398). Finally, we could not include all possible contextual determinants that might affect old-age survival and active ageing. Social support, certain housing conditions and physical environmental exposures (e.g. noise, aesthetics, concrete heatwaves and cold spells) and the other dimensions of access to healthcare are from our point of view critical determinants that we disregarded, due to lack of data at ecological level.

6.5. Policy implications

Our study was not interventional, so that we cannot uncover which interventions would bring the most benefits. Still, the identification of worst-off and better-off areas and neighbourhoods is in our opinion a first step towards the development of equity-oriented policies. Indeed, identifying priorities is the first step in the elaboration of any public health intervention (399). If we aim to reduce health differences, the more vulnerable populations should receive extra attention; that of course hand in hand with the aim of improving overall population expectancy. Very few studies had put on a map where deprivation pockets are, where harmful environments exist, where healthcare provision is worst, and where people live longer or lesser. Most studies only disclose rates ranges and relative inequality measures. Yet, health policy is highly regionalized. Hopefully our work would aid in the process of allocating resources to boost economic and social development in certain areas. European regional funds (European Regional Development, Cohesion, and Social Fund) could be directed to these specific areas. Portugal stood out as one of the countries with the lowest old-age survival rates. The amazing evolution of the Portuguese life expectancy at birth, achieved with policies that dramatically reduced infant mortality, should be seen as an enticement to improve health indicators among the oldest too.

Understanding the causes of geographical disparities is essential to delineate effective policy. Our study suggests that it should be given priority to the reduction of between-area differences in term of socioeconomic characteristics. The reduction of socioeconomic inequality is not only a moral question, but it comes with costs to society. We found a substantial number of deaths could be avoided (180,000 per decade in a more conservative scenario to 800,000 more optimistically) and, although we have not assessed financial costs, there will be certainly economic benefits in reducing differences between social groups. According to Mackenbach et al and looking at all-age strata and the entire Europe, the costs of health inequalities are estimated at 980 billion euros every year (9.4% of the gross domestic product) (400). There is also evidence that reducing inequalities benefits not only disadvantaged groups but also the whole society (42).

Although the association of socioeconomic disadvantage and poor health is the most solid finding among all social determinants, there is still no effective policy and health intervention. The WHO Europe has suggested different strategies to reduce socioeconomic disparities in Europe (148, 401, 402): i) boost economic growth especially in disadvantaged areas and communities; ii) tackle income inequalities through a better redistribution of income and public financing of key areas (health, education, transport); iii) tackle poverty (lack of essential assets); iv) promote easy and similar access to education; v) improving physical environments; vi) make healthcare more equitable and reduce financial and geographical barriers; among others. Specifically for the older population groups, our population target, police makers should ensure all have a minimum standard income that cover all the expenses required for a healthy lifestyle, which includes diet, exercise, heating/cooling in the house, medical care, etc. Issues such as isolation and social exclusion should be addressed too (148, 402). The access to healthcare was also found to be lower in more disadvantaged areas. This trend, "inverse health law", was observed in Portugal but it has been reported since the 1970s almost universally (372). By improving those services and by tackling this form of environmental injustice we might be able to minimize the effect of deprivation.

We also recommend a close monitoring of health inequalities at local level. As our study demonstrated, regional indicators obscure many important differences. Apropos we appeal to the creation of a common geography in all Europe. NUTS (Nomenclature of Territorial Units for Statistics) were a first attempt to harmonize geographic divisions but smaller areas should be used. Inequality should be measured, using comparable indicators and units of analysis, and should be monitored in all nations, putting particular emphasis on the urban areas which experience the widest inequalities and, simultaneously, the fastest population growth. Policies and objectives should be measurable; otherwise they are condemned to failure. Monitoring and action had better be the responsibility of both governmental and academic institutions, in strong collaboration, to provide more compressive portraits of the extent of the health inequalities and to provide prompt answers to the real societal problems.

We were able to confirm built environment affect old population health-related behaviours like PA which, in turn, might impact old-age survival, functional status, and quality of life. Built environment is highly malleable and interventions to improve physical environments (contrasting to the social context) tend to be straightforward and relatively easy to implement specially at municipality level. Municipalities have a certain degree of governance independence and might promptly respond to the population necessities (403). In Porto we found that the creation of parks and the guarantee of easy access to services and equipment might lead to an increase in the PA levels of seniors, and possibly of other population groups, as nature and outdoor places are the preferable sites for engaging in PA among all strata of adult population (259). When comes to PA, this thesis also showed that built environment is not the only culprit to the sedentary lifestyles that predominate in our societies especially among the older. Multi-facet interventions, anchored in social-ecological models, should be envisaged too.

6.6. Future research

Numerous questions remained unanswered in this thesis. To name a few, some research questions that require further research are the following:

- Which other determinants might be involved in the spatial differences in old-age survival?
- Do healthy-life expectancy and disability life expectancy in late life follows a similar geographical patterning in Europe, Portugal and Porto? Which factors contribute most for the observed inequalities?
- Are the causes of death later in life similar in better-off and worst-off geographical areas?
- What is truly behind the cross-national differences in the effect of socioeconomic deprivation? Welfare and healthcare provision? Geopolitical divides and socio-spatial segregation? Social support? Or other buffering mechanism?
- What is the reason behind the larger spatial segregation in old-age survival in Porto in comparison to Lisbon Metropolitan Area?
- Why built environmental characteristics affect differently men and women?
- What is the role of micro-environmental features (rest places, squares, trash) on the PA levels of the older adults?
- Would the conclusions be the same if we have assessed the longitudinal relation between neighbourhood environments and PA? Would the association between park proximity and PA remain if we considered their quality and characteristics?

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8. Appendixes

Appendix 1

Supplementary material 1: Correspondence between variables in the Portuguese 2001 census and the EU-SILC survey.

EU-SILC survey	Portuguese 2001 Census	Recodifications to guarantee matching between EU-SILC and census
Code/name	**Code/name***	
HH020: Tenure status 1-owner 2- tenant or subtenant paying rent at prevailing or market rate 3- accommodation is rented at a reduced rate (lower price that the market price) 4 - accommodation is provided free	AFCRHPO – Owned household AFCRHARR – Rented (regardless the price) household AFCRH – total households	Census variables were grouped to match EU-SILC: AFCRHPO – Owned household (EU-SILC 1) AFCRHARR – Rented (regardless the price) household (EU-SILC 2-3) AFCRH –(AFCRHPO+ AFCRHARR) – other situations (EU-SILC 4)
HH080: Bath or shower in dwelling 1-yes 2- no	AFRHBN – Households with bath/shower	None.
HH090: Indoor flushing toilet for sole use of household 1-yes 2- no	AFRHRE – Households with indoor flushing	None.
RB080: Year of birth Continuous variable	HR15_19-resident male aged 15-19 yrs MR15_19- resident female aged 15-19 yrs HR20_64- resident male aged 20-64 yrs MR20_64- resident female aged 20-64 yrs HR65-resident male aged 65 yrs or more MR65- resident female aged 65 yrs or more	EU-SILC variables were grouped to match census: 1- resident male aged 15-19 yrs (census HR15_19) 2- resident female aged 15-19 yrs (census MR15_19) 3- resident male aged 20-64 yrs (census HR20_64) 4- resident female aged 20-64 yrs (census MR20_64) 5- resident male aged 65 yrs or more (census HR65) 6- resident female aged 65 yrs or more (census MR65)
RB090: Sex 1-male 2-female	HR15_19+ HR20_64 + HR65 – resident males MR15_19 + MR20_64 + MR65 – resident females	
PL020: Actively looking for a job 1-yes 2-no	Unemployed resident population looking for a job in the last 30 days†	None.

PL050: Occupation (ISCO-88 (COM)) ‡ Code (2 digits)	IR_SP – employed in the primary sector IR_SS – employed in the secondary sector IR_ST– employed in the tertiary sector	EU-SILC variables were grouped to match census: 1-Primary sector – ISCO-88=61 (census IR_SP) 2-Secondary sector – ISCO-88=01-71 (census IR_SS) 3-Terciary sector – ISCO-88=11-52 (census IR_ST)
HH030: Number of rooms available to the household 1-5 number of rooms 6 – 6 or more rooms	households with 5 rooms or less† households with 6 rooms or more	EU-SILC variables were grouped to match census: 1-households with 5 rooms or less[c] (H5) 2-households with 6 rooms or more (H5)
PE040: Highest ISCED-97§ level attained 0-pre-primary education 1-primary education 2- lower secondary education 3-(upper) secondary education 4- post-secondary non tertiary education 5- first stage of tertiary education and second stage of tertiary education	IRQA_110 – 1^{st} -4^{th} grades IRQA_120 –5^{th}-6^{th} grades IRQA_130 – 7^{th}-9^{th} grades IRQA_200 – 10^{th}-12^{th} grades IRQA_300 – medium education IRQA_400 – university	Census variables were grouped to match EU-SILC: IRQA_110+ IRQA_120- primary education (EU-SILC 1) IRQA_130- lower secondary education (EU-SILC 2) IRQA_200-(upper) secondary education (EU-SILC 3) IRQA_300 – post-secondary non tertiary education (EU-SILC 4) IRQA_400 – first stage of tertiary education and second stage of tertiary education (EU-SILC 5)

*Answer categories do not fully match those in the 2001 Census questionnaire; these categories are those made available by Statistics Portugal (confidentiality issues).
†These variables were obtained upon request; they were not freely available (no code assigned).
‡International Standard Classification of Occupations, published by the International Labour Force (Geneva, 1990).
§International Standard Classification of Education 1997.

Appendix 2

S1. Supplementary table – Summary assessment of the health-relevance of environmental factors.

Environmental factor	Examples of typical risks reported (and corresponding 95% CI)[a]
Outdoor air Pollution Clear association between short- and long-term exposure to outdoor air pollutants and mortality (cardiovascular, respiratory and all-cause) (1-3).	Meta-analysis % excess all-cause mortality (1): PM_{10} - 2.0 (95% CI 1.5-2.4) per 31.3 µg/m^3 CO - 1.7 (1.2-2.2) per 1.1 ppm NO_2 - 2.8 (2.1-3.5) per 24.0 ppb O_3 - 1.6 (1.1-2.0) per 31.2 ppb SO_2 - 0.9 (0.7-1.2) per 9.4 ppb
Green areas Green space availability affects health two ways: shaping exercise habits (4, 5) and directly affecting morbidity and mortality (6, 7). Recent reviews report there is moderate evidence of a relationship between green space availability and health and health-related behaviors (8-13)	RR for lack of green space vs. high availability (6): Ischemic heart disease - 1.19 (1.11-1.28) Cerebrovascular disease - 1.25 (1.11-1.40)
Climate Both cold and heat extremes are related with mortality, especially cardiorespiratory (14, 15). In Portugal, effects of heat and heat waves have been thoroughly studied (16-18).	Heat: % excess mortality per unit increase in temperature: Portugal – 2.1 (1.6-2.5) Lisbon and 1.5 (1.0-1.9) Porto (16) Worldwide (meta-analysis) – 1-3% (14) Cold: % excess mortality per unit drop in temperature: Europe (6 countries): from 2.15 (1.20-3.10) to 0.27 (0.15-0.40) (15)
UVB Effects of UVB are of two types: UVB is the leading risk factor for skin cancer (19, 20), but it is also essential in vitamin D synthesis and, thus, protective against different types of cancer (21, 22).	Skin cancer (harmful): Meta-analysis RR (19): intermittent sun exposure (1.61, 1.31- 1.99); sunburn history (2.03, 1.73-2.37); total sun exposure (1.34, 1.02-1.77) Cancer mortality (protective): OR (highest vs. lowest sunlight exposure) (22): prostate (0.90, 0.87-0.93); breast (0.74, 0.72-0.76); ovarian (0.84, 0.81-0.88); colon (0.73, 0.71-0.74)

Indoor Radon Strong evidence links lung cancer and radon exposure, being the second leading risk factor for lung cancer (23-27).	Meta-analysis % excess lung cancer per 100 Bq/m^3 increase: Europe (8.4, 3.0-15.8); USA (11, 1-28) (24, 25)
Industrial facilities Proximity (within ~3 km radius) to waste management sites, chemical industries, metal and mineral manufactures and combustion installations is associated with increased risk of cancer, adverse birth outcomes and cardiovascular disease (28-31). Residing near food or paper industries seems to have null/limited health effects.	Risk in the proximity of: Incinerator – 3.5% excess risk of cancer (30) Landfill – 2-6% excess risk of congenital anomalies and low birth weight (30) Chemical industries (n=28) – RR of 1.7 (1.0-3.0) of leukemia (28) Metal industries –HR=1.52 for all-cause mortality; 1.77 for ischemic heart disease (31) Coke plant (combustion) - OR=2.05 (1.07-3.93) for lung cancer (29)
Drinking water quality There is strong evidence of a relationship between THM in drinking water and cancer (32, 33). While much less studied, significant associations between nitrates and cancer (eg. bladder) have been reported (34, 35). Exposure to heavy metals (aluminum, magnesium, arsenic, manganese) is associated with adverse neurological outcomes, namely Alzheimer disease (36, 37). Water hardness (especially magnesium) is known to be protective against cardiovascular disease (38).	THM: Bladder cancer (meta-analysis) – OR=1.47 (1.05-2.05) for exposure >50μg/l vs. ≤5μg/l (33) Colon cancer (meta-analysis) – OR=1.27 (1.08-1.50) (32) Rectal cancer (meta-analysis) – OR=1.30 (1.06-1.59) (32) Nitrates (highest vs. lowest exposure) (39): Gastric cancer: OR=1.16 (1.05–1.29) Water hardness (magnesium): Cardiovascular mortality (meta-analysis): OR=0.75 (0.68 - 0.82) for those in the highest exposure class (38).
Noise Noise has been consistently associated with cardiovascular morbidity and emotional stress (40, 41).	Meta-analysis RR for 5Db(A) increase in noise (40): hypertension (1.26, 1.14-1.39); ischemic heart disease (1.09, 1.05-1.13).

[a]When existent, meta-analysis and results from southern Europe are preferentially cited; ppm=parts per million; ppb=parts per million; Bq=Becquerel; THM=trihalometanes; OR=odds ratio; RR=relative risk; HR=hazard ratio; 95% CI – 95% confidence interval.

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Development of a measure of multiple physical environmental deprivation. After United Kingdom and New Zealand, Portugal.

Appendix 3

S2. Supplementary table – Overview table comparing Portuguese (PT-MEDIx), United Kingdom (UK-MEDIx) and New Zealand (NZ-MEDIx) environmental deprivation indexes

	PT-MEDIx	UK-MEDIx	NZ-MEDIx
No. of geographic units	278	10,654	1860
Average population per geographic unit	36,000	5518	2300
No. of included variables	8	8	4
No. of beneficial variables	1	2	2
No. of detrimental variables	7	6	2
Index range	-1 to +4	-2 to +3	-2 to +2
Proportion of the population living in the least environmentally deprived areas	3.4%	1.6%	18.2%
Proportion of the population living in the most environmentally deprived areas	20.1%	0.4%	21.1%
Control for socioeconomic deprivation	YES	YES	YES
Control for health-related behaviors	NO	NO	YES

Development of a measure of multiple physical environmental deprivation. After United Kingdom and New Zealand, Portugal.

Appendix 4

Supplementary material 1. Characteristics of the population data.

Country	1991	2001	2011	Type
Andorra	31st December	31st December	31st December	Annual census (parish register)
Austria	15th May	15th May	31st October	Decennial census
Belgium	1st March	1st October	1st January (2012)	Decennial census (2011 - national register)
Denmark	1st January	1st January	1st January	Annual census (national register)
Finland	31st December	31st December	31st December	Annual census (national register)
France	5th March (1990)	8th March (1999)	1st January (2009)	Decennial census (2009 – annual census/estimates)
Italy	20th October	21st October	9th October	Decennial census
Liechtenstein	31st December	31st December	31st December	Decennial census (estimate)
Luxemburg	1st March	15th February	1st February	Decennial census
Malta	1st January	1st January	1st January	Eurostat (estimates)
Netherlands	1st January	1st January	1st January	Administrative register
Norway	1st January	31st December	19th November	Decennial census + Administrative register
Portugal	15th April	12th March	21st March	Decennial census
San Marino	31st December	31st December	31st December	Administrative register
Spain	1st March	1st November	1st November	Decennial census
Sweden	31st December	31st December	31st December	Annual census (national register)
Switzerland	4th December (1990)	5th December (2000)	31st December	Decennial census (2011 - administrative register)
United Kingdom	21st April	29th April	27th March	Decennial census

Where do people live longer and shorter lives? An ecological study of old-age survival across 4404 small areas from 18 European countries.

Appendix 5

Supplementary material 2. Statistical modelling.

The likelihood

The data we have used was the number of people aged 75-84 years in 1991 and 2001 and the number of people aged 85-94 years old in 2001 and 2011, for each gender and area.

Our aim was to define a model for the survival rate:

$$r_{k,i,t} = y_{k,i,t} / n_{k,i,t-10}$$

for k=1,2, representing gender, i=1,...,4404, representing area, and t=2001,2011, representing the census year. The variable 'y' represents the population aged 85-94 years old and 'n' represents the population aged 75- 84 years old. For France, the census took place in the years 1990, 1999 and 2009; so there is an interval of nine years in the first period we considered.

Because of that difference, we used the clustered/clumped Binomial model, Cbinomial(m,d,p). To use this model, we have to consider the deaths instead survival counts. This model is defined as follows. Suppose that 'z' represents the death probability of a person and it is Binomial(d,p) distributed, where 'p' is the death probability of that person after one year and 'd ' is the number of years of the period under analysis. Then, to define the variable 'u', we assume 0 when z=0 and 1 if z>0. It gives $P(u=0) = (1 - p)^d$ and $Prob(u=1) = 1 - (1 - p)^d$. It happens that for each area we have 'm' persons in the beginning of the period. So, let $y = u_1 + \ldots + u_k$ the number of persons who died at the end of the period of 'd' years. This variable, y, is Cbinomial(m,d,p). In our study, we have d=9 for France in the first period under analysis and d=10 for all other countries and periods.

The linear predictor structure

There were tested 80 different structure models. The basic model was just a Generalized Linear Model, as we have modeled the rate considering gender and year only. The other models were built taking into account the spatial structure, with and without interactions with gender and year. Moreover, an independent (unstructured) random effect was considered, and we allowed it to vary by area 'i', by area and gender 'ki', by year and area 'it', and by area, gender and year 'kit'. So, we created five scenarios to evaluate the unstructured random effect (URE) 'u': one without it and four different variations units for the URE. Considering the spatially structured random effect (SSRE)'s', we considered the scenario without SSRE and fifteen scenarios for having any kind of SSRE. By combining these 5x16 scenarios we ended up fitting 80 models to our data.

The SSRE models we evaluated consider different interaction structures from a basic model and the four groups formed by gender and year. The basic model is just the Besag's model varying over areas 'i', considering the graph defined by the neighborhood structure from the map. So, when considering this model and the URE by area 'i' we have the well know BYM model, Besay, York and Molie' (1991) and the linear predictor considering gender, year, u_i and s_i can be written as

$$\eta_{kit} = \beta_0 + \beta_1 gender_{kit} + \beta_2 year{kit} + s_i + u_i$$

The DIC (Deviance Information Criteria) for this model can be found in the second line and second column of Table 2 and summing with the DIC from the model with minor DIC.

All SSRE structures we defined considering the basic model s_i are listed in the Table 1. Table 2 shows the DIC difference from each model and the model with minor DIC (best model).

Table 1 – Description for the spatially structured random effect.

Name	Description
s0	no SSRE
s1	SSRE as the basic one, s_i, when it follows the Besag intrinsic conditional autoregression
	replications of the basic SSRE model
rg	s_i is replicated over gender as s_ki. One SSRE for each gender, with same precision.
ry	s_i is replicated over year as s_it. One SSRE for each year, with same precision.
rgy	s_i is replicated over gender and year as s_kit. One SSRE for each gender and one for each year, all with same precision. It results into in four independent maps
	shared SSRE over groups defined by gender or year or gender and year
sg	s_i is shared between gender as s_ki = s_i(women) + \rho s_i(men)
sy	s_i is shared between year as s_it = s_i(2001) \rho s_i(2011)
sgy	s_i is shared between gender and year as s_kit = s_i(women,2001) + \rho1 s_i(men) + \rho2 s_i(2011)
	replicated/shared SSRE over gender + replicad/shared SSRE over year
rgry	rg and ry as s_kit = s1_i(women) + s1_i(men) + s2_i(2001) + s2_i(2011). One SRRE for each gender and year. Different from 'rgy', as it has two precisions, one for gender and one for year.
rgsy	rg and sy as s_kit = s1_i(women) + s1_i(men) + s2_i(2001) + \rho s2_i(2011). One SRRE for each gender + one shared SRRE across year.
sgry	sg and ry as s_kit = s1_i(women) + \rho1 s1_i(men) + s2_i(2001) + s2_i(2011). One shared SRRE across gender + one SRRE replicated for each year.
sgsy	sg and sy as s_kit = s1_i(women) + \rho1 s1_i(men) + s2_i(2001) + \rho2 s2_i(2011). One shared SRRE across gender + one shared SRRE across year.
	replicated/shared SSRE over gender or year + shared across gender and year
rg.sgy	rg and sgy as s_kit = s1_i(women) + s1_i(men) + s2_i(women,2001) + \rho1 s_i(men) + \rho2 s_i(2011). A SSRE for each gender plus a shared SSRE across gender and year.
sg.sgy	sg and sgy as s_kit = s1_i(women) + \rho1 s1_i(men) + s2_i(women,2001) + \rho2 s_i(men) + \rho3 s_i(2011). A shared SSRE across gender plus a shared SSRE across gender and year.
ry.sgy	ry and sgy as s_kit = s1_i(2001) + s1_i(2011) + s2_i(women,2001) + \rho1 s_i(men) + \rho2 s_i(2011). A SSRE for each year plus a shared SSRE across gender and year.
sy.sgy	sy and sgy as s_kit = s1_i(2001) + \rho1 s1_i(2011) + s2_i(women,2001) + \rho2 s_i(men) + \rho3 s_i(2011). A shared SSRE across year plus a shared SSRE across gender and year.

To assess which structure was the best, we considered a computationally faster but less accurate approach available in the R-INLA package. Latter we have used a more accurate approach for the three best models. For the faster approach we considered the Gaussian approximation for the random effects posterior marginals. This approach is problematic if we have low counts. In our case, we have only 61 (out of 17 616) observations less than five. We have also plugged in the posterior mode for the hyper-parameters to compute the marginals of the random effects, which is an Empirical Bayes integration strategy, not a full Bayes.

In Table 2 we have the DIC difference of each model we fitted, and the DIC of the model with minor DIC value. The model with minor DIC has SSRE effect correlated across gender (the same for each year) and URE for each gender, area and year. This DIC value is approached as 153374.2 for the results on Table 2.

Table 2 – DIC difference from each model and the one (153374.2) for the model with minor DIC.

	i0	**i**	**ki**	**it**	**kit**
s0	271316.8	28354.5	18748.1	13578.6	503.3
s1	86779.6	28320.0	18574.6	13465.1	16.3
rg	79773.5	20475.6	18636.9	5599.4	192.9
ry	74691.3	15877.3	6107.7	13505.7	164.5
rgy	65966.8	5735.4	3921.5	3076.7	301.0
sg	85480.2	20528.2	18573.9	5821.3	0.0
sy	86835.2	15882.5	6297.9	13464.4	10.6
sgy	169216.3	15815.6	6404.5	5800.1	290.6
rgry	66537.6	8095.0	6114.1	5603.1	161.0
rgsy	67213.8	8015.1	6189.5	5618.5	19.7
sgry	65696.8	7927.1	6128.0	5655.5	2.0
sgsy	72760.9	8061.8	6120.7	5594.5	11.2
rg.sgy	67197.9	8092.9	6301.5	5599.3	197.9
sg.sgy	72631.6	8145.3	6217.8	5609.7	1.1
ry.sgy	65204.2	8105.0	6096.4	5749.5	171.6
sy.sgy	73209.5	8084.3	6115.6	5670.8	10.2

When considering the DIC to select a model, we can see that the three models with the minor values are quite similar: the difference between the first and the second is 1.1, and between the first and the third is 2.0. The second better model is the model with two SSRE, one correlated across gender and another correlated across gender and year. The third better model has two SSRE, one shared across gender and another replicated over the years.

For the three models with lower DIC values on Table 2, we also considered the simplified Laplace approximation for the random effect posterior marginals and CCD (Central Composite Design) integration strategy over the hyper-parameters. These settings on R-INLA are the default choice and are more expensive than the ones used for all 80 models. Using the results computed considering the 'simplified.laplace' for the random effects and the 'ccd' integration strategy we have DIC values equals to 153336.7, 153337.3 and 153338.1, respectively. That confirms the best model is the one with the shared spatial effect between gender, plus an independent random effect for each gender, year and area.

Where do people live longer and shorter lives? An ecological study of old-age survival across 4404 small areas from 18 European countries.

Appendix 6

Supplementary material 3. Areas with significantly high/low survival rate.

a) Women 2001

LOW SURVIVAL			
GEOCODE	**NAME**	**COUNTRY**	**SURVIVAL RATE**
E09000019	Islington	UK	25.4
E09000030	Tower Hamlets	UK	25.8
E09000022	Lambeth	UK	26.4
BE502	Colfontaine	BE	26.9
PT4205	Ribeira Grande	PT	27.5
E09000025	Newham	UK	27.6
BE509	Frameries	BE	27.7
FR284	Sarreguemines	FR	27.7
E09000028	Southwark	UK	27.9
E09000007	Camden	UK	28.5
E41000324	City of London·Westminster	UK	28.5
ES14	Alpujarras	ES	28.6
IT111	Caivano	IT	28.7
BE354	Saint-Josse-ten-Noode	BE	28.7
IT9	Afragola	IT	29.2
IT238	Gela	IT	29.5
FR133	Forbach	FR	29.8
AU2449	Oberpullendorf	AU	29.9
E08000012	Liverpool	UK	29.9
FR73	Cambrai	FR	30.0
FR263	Saint-Denis	FR	30.1
E08000003	Manchester	UK	30.2
E09000032	Wandsworth	UK	30.3
E09000012	Hackney	UK	30.4
E09000013	Hammersmith and Fulham	UK	30.4
IT402	Palma Campania	IT	30.4
E09000018	Hounslow	UK	30.7
E09000023	Lewisham	UK	30.8
FR59	Boulogne-sur-Mer	FR	31.0
FR90	Châteaulin	FR	31.0
E09000014	Haringey	UK	31.1
E06000012	North East Lincolnshire	UK	31.1
E07000123	Preston	UK	31.1
E09000031	Waltham Forest	UK	31.6
S12000046	Glasgow City + South Lanarkshire	UK	32.4

HIGH SURVIVAL			
GEOCODE	NAME	COUNTRY	SURVIVAL RATE
ES174	Lozoya Somosierra	ES	67.1
ES142	Guadarrama	ES	66.8
ES300	Sur Occidental (Madrid)	ES	59.3
ES40	Baix Penedès	ES	58.9
CH114	Vallemaggia	CH	57.9
AND82	Escaldes	AD	56.9
BE433	Ottignies-Louvain-la-Neuve	BE	56.6
AND79	Andorra	AD	56.4
FR246	Rambouillet	FR	56.1
ES64	Campiña (Madrid)	ES	53.8
NLGM0321	Houten	NL	53.7
BE83	Wommelgem	BE	53.6
BE4	Kalmthout	BE	52.8
BE117	Nazareth	BE	52.7
ES168	Llanada Alavesa	ES	52.7
IT629	Vicenza Sud-Est	IT	52.1
PT1510	Seixal	PT	52.1
IT362	Montesilvano	IT	52.0
CH121	Lavaux-Oron	CH	51.6
ES63	Campiña (Guadalajara)	ES	51.4
SE1384	Kungsbacka	SE	51.4
IT494	San Lazzaro di Savena	IT	51.2
CH7	Meilen	CH	51.1
SE162	Danderyd	SE	50.7
ES266	Segovia	ES	50.6
IT446	Portogruarese	IT	50.4
ES296	Soria	ES	50.3
ES261	Salamanca	ES	50.0
SE186	Lidingö	SE	50.0
IT438	Pordenone Est	IT	50.0
IT382	Oderzo	IT	49.9
IT564	Trento Centro Nord	IT	49.7
NLGM1581	Utrechtse Heuvelrug	NL	49.6
IT177	Conegliano (SUD)	IT	49.6
IT204	Faenza	IT	49.5
IT22	Alta Padovana (Sud Est)	IT	49.5
ES330	Vegas (Madrid)	ES	49.5
IT406	Parma Sud-Est	IT	49.4
IT442	Pordenone Urbano	IT	49.3
ES112	Cuenca de Pamplona	ES	49.2
IT637	Vittorio Veneto (NORD)	IT	49.0
IT293	Lugo	IT	49.0
IT424	Pianura Est	IT	48.9
ES28	Arlanzón	ES	48.9
IT224	Forlì	IT	48.4

b) Women 2011

LOW SURVIVAL			
GEOCODE	**NAME**	**COUNTRY**	**SURVIVAL RATE**
DN400	Bornholm	DN	22.5
E09000030	Tower Hamlets	UK	30.3
E09000012	Hackney	UK	30.5
BE354	Saint-Josse-ten-Noode	BE	30.6
E09000025	Newham	UK	32.5
E09000013	Hammersmith and Fulham	UK	33.3
E09000028	Southwark	UK	33.4
DN101	Copenhagen	DN	34.4
E06000021	Stoke-on-Trent	UK	34.9
E09000022	Lambeth	UK	34.9
E08000011	Knowsley	UK	35.2
E08000003	Manchester	UK	35.2
ES14	Alpujarras	ES	35.3
E09000019	Islington	UK	35.3
E09000002	Barking and Dagenham	UK	35.3
BE502	Colfontaine	BE	35.7
E09000014	Haringey	UK	35.9
E08000012	Liverpool	UK	36.0
E07000120	Hyndburn	UK	36.0
S12000045	East Dunbartonshire + North Lanarkshire	UK	36.2
ES96	Ceuta	ES	36.2
E06000039	Slough	UK	36.4
E09000011	Greenwich	UK	36.4
S12000005	Clackmannanshire	UK	36.5
S12000008	East Ayrshire	UK	36.6
S12000046	Glasgow City + South Lanarkshire	UK	36.6
E07000027	Barrow-in-Furness	UK	36.7
E06000010	Kingston upon Hull· City of	UK	36.9
E08000006	Salford	UK	37.0
E08000010	Wigan	UK	37.1
NLGM0928	Kerkrade	NL	37.1
DN360	Lolland	DN	37.2
E09000020	Kensington and Chelsea	UK	37.4
E09000023	Lewisham	UK	37.5
E06000002	Middlesbrough	UK	37.5
E09000024	Merton	UK	37.6
E08000021	Newcastle upon Tyne	UK	37.7
E08000024	Sunderland	UK	37.8
E08000020	Gateshead	UK	37.9
S12000014	Falkirk	UK	37.9

GEOCODE	NAME	COUNTRY	SURVIVAL RATE
E08000008	Tameside	UK	38.0
NLGM0363	Amsterdam	NL	38.0
E06000009	Blackpool	UK	38.0
S12000033	Aberdeen City	UK	38.0
E09000009	Ealing	UK	38.1
E09000032	Wandsworth	UK	38.2
E08000001	Bolton	UK	38.2
S12000035	Argyll & Bute + West Dunbartonshire	UK	38.3
E08000025	Birmingham	UK	38.6
E08000035	Leeds	UK	39.0

HIGH SURVIVAL			
GEOCODE	NAME	COUNTRY	SURVIVAL RATE
ES300	Sur Occidental (Madrid)	ES	71·5
ES142	Guadarrama	ES	69.8
ES40	Baix Penedès	ES	68.0
PT510	Vila de Rei	PT	67.9
ES174	Lozoya Somosierra	ES	65.9
ES63	Campiña (Guadalajara)	ES	65.5
FR246	Rambouillet	FR	65.4
FR209	Muret	FR	64.7
FR35	Barcelonnette	FR	64.6
ES64	Campiña (Madrid)	ES	64.2
FR237	Poitiers	FR	63.9
BE21	Malle	BE	63.7
FR44	Bellac	FR	63.6
BE356	Horebeke	BE	63.5
BE83	Wommelgem	BE	62.1
FR77	Castelsarrasin	FR	62.0
FR115	Digne-les-Bains	FR	61.9
FR259	Sables-d'Olonne	FR	61.9
FR70	Cahors	FR	61.9
ES296	Soria	ES	61.4
FR136	Gap	FR	61.3
FR171	Lodève	FR	61.2
ES130	Fuerteventura	ES	61.1
BE127	Boechout	BE	61.0
BE373	Maarkedal	BE	61.0
FR256	Rodez	FR	60.8
FR7	Alençon	FR	60.6
FR19	Arcachon	FR	60.5
FR40	Bayonne	FR	60.5
FR93	Château-Thierry	FR	60.4
FR228	Palaiseau	FR	60.3

GEOCODE	NAME	COUNTRY	SURVIVAL RATE
ES28	Arlanzón	ES	60.3
BE108	Aartselaar	BE	60.3
FR120	Draguignan	FR	60.2
FR255	Rochefort	FR	60.2
FR257	Romorantin-Lanthenay	FR	60.1
FR27	Aurillac	FR	59.9
FR242	Privas	FR	59.9
FR41	Beaune	FR	59.9
FR271	Saint-Germain-en-Laye	FR	59.8
FR128	Figeac	FR	59.6
FR131	Fontainebleau	FR	59.5
FR3	Aix-en-Provence	FR	59.4
FR191	Millau	FR	59.3
FR233	Périgueux	FR	59.3
FR38	Bastia	FR	59.2
FR116	Dijon	FR	59.1
FR286	Saumur	FR	59.1
FR85	Chartres	FR	59.0
FR23	Arles	FR	59.0
ES330	Vegas (Madrid)	ES	59.0
FR80	Châlons-en-Champagne	FR	59.0
IT382	Oderzo	IT	58.9
FR178	Mâcon	FR	58·6
FR164	Lesparre-Médoc	FR	58.6
FR20	Argelès-Gazost	FR	58.6
FR236	Pithiviers	FR	58.5
FR313	Vannes	FR	58.5
FR26	Auch	FR	58.4
FR60	Bourg-en-Bresse	FR	58.3
FR82	Chambéry	FR	58.3
ES261	Salamanca	ES	58.3
FR325	Villeneuve-sur-Lot	FR	58.2
FR179	Mamers	FR	58.2
FR324	Villefranche-sur-Saône	FR	58.1
ES168	Llanada Alavesa	ES	58.0
FR48	Besançon	FR	57.8
FR154	La Rochelle	FR	57.8
FR232	Pau	FR	57.8
FR155	La Roche-sur-Yon	FR	57.8
FR56	Bordeaux	FR	57.8
FR127	Évry	FR	57.7
FR243	Provins	FR	57.7
IT494	San Lazzaro di Savena	IT	57.7
FR206	Mortagne-au-Perche	FR	57.7
FR198	Montbrison	FR	57.6
FR66	Brignoles	FR	57.5

GEOCODE	NAME	COUNTRY	SURVIVAL RATE
FR15	Angoulême	FR	57.5
FR172	Lons-le-Saunier	FR	57.5
FR307	Tours	FR	57.5
ES309	Tierras de León	ES	57.4
FR296	Tarbes	FR	57.4
ES258	Sagra-Toledo	ES	57.4
FR14	Angers	FR	57.4
FR182	Marmande	FR	57.3
FR101	Clermont-Ferrand	FR	57.3
FR306	Tournon-sur-Rhône	FR	57.3
IT157	Chieri	IT	57.2
FR6	Albi	FR	57.2
ES256	Rioja Media	ES	57.2
FR195	Montauban	FR	57.2
ES112	Cuenca de Pamplona	ES	57.1
FR253	Roanne	FR	56.9
FR220	Niort	FR	56.9
FR203	Montpellier	FR	56.9
ES91	Centro (Valladolid)	ES	56.9
ES327	Vallès Oriental	ES	56.8
FR240	Pontoise	FR	56.8
FR17	Antony	FR	56.8
FR69	Caen	FR	56.5
FR227	Orléans	FR	56.5
FR305	Toulouse	FR	56.1

c) **Men 2001**

	LOW SURVIVAL		
GEOCODE	**NAME**	**COUNTRY**	**SURVIVAL RATE**
FR163	Lens	FR	16.6
FR312	Valenciennes	FR	16.8
FR284	Sarreguemines	FR	16.9
FR300	Thionville-Ouest	FR	16.9
E09000030	Tower Hamlets	UK	17.2
FR283	Sarrebourg	FR	17.4
E09000019	Islington	UK	17.6
NLGM0984	Venray	NL	17.8
FR57	Boulay-Moselle	FR	17.8
FR204	Montreuil	FR	18.7
FR148	Issoudun	FR	18.9
FR133	Forbach	FR	18.9
E09000028	Southwark	UK	18.9
E06000012	North East Lincolnshire	UK	18.9
FR145	Haguenau	FR	19.3
FR49	Béthune	FR	19.4
E09000014	Haringey	UK	19.4
E09000012	Hackney	UK	19.4
FR205	Morlaix	FR	19.6
E09000022	Lambeth	UK	19.6
E08000006	Salford	UK	19.6
E09000032	Wandsworth	UK	19.6
FR144	Guingamp	FR	19.7
E08000003	Manchester	UK	19.7
FR90	Châteaulin	FR	19.9
E06000008	Blackburn with Darwen	UK	20.0
FR279	Saint-Omer	FR	20.1
E09000025	Newham	UK	20.3
S12000046	Glasgow City + South Lanarkshire	UK	20.4
E08000012	Liverpool	UK	20.5
E08000010	Wigan	UK	20.8

HIGH SURVIVAL			
GEOCODE	NAME	COUNTRY	SURVIVAL RATE
AND82	Escaldes	AD	48.2
ES142	Guadarrama	ES	44.1
AND79	Andorra	AD	42.2
ES64	Campiña (Madrid)	ES	40.9
ES300	Sur Occidental (Madrid)	ES	40.1
ES63	Campiña (Guadalajara)	ES	39.0
ES174	Lozoya Somosierra	ES	37.9
FR246	Rambouillet	FR	37.4
CH7	Meilen	CH	37.3
ES40	Baix Penedès	ES	37.2
ES32	Ávila	ES	37-1
E07000226	Crawley	UK	37.0
ES8	Aliste	ES	36.8
ES296	Soria	ES	36.7
ES261	Salamanca	ES	36.2
SE162	Danderyd	SE	36.1
ES266	Segovia	ES	36.0
CH135	Sierre	CH	35.9
ES301	Sureste (Valladolid)	ES	35.9
ES150	Hoya de Teruel	ES	35.5
ES336	Vitigudino	ES	35.4
ES81	Campos-Pan	ES	34.6
ES220	Orense	ES	34.5
ES309	Tierras de León	ES	34.4
ES168	Llanada Alavesa	ES	34.3
ES62	Camp de Tarragona	ES	34.1
CH144	Genève	CH	33.7

d) Men 2011

LOW SURVIVAL			
GEOCODE	NAME	COUNTRY	SURVIVAL RATE
DN400	Bornholm	DN	16.4
BE354	Saint-Josse-ten-Noode	BE	19.1
IT51	Arzano	IT	22.8
DN101	Copenhagen	DN	23.1
E09000030	Tower Hamlets	UK	23.6
BE502	Colfontaine	BE	23.9
NLGM0882	Landgraaf	NL	23.9
NLGM0899	Brunssum	NL	24.4
NLGM0928	Kerkrade	NL	24.6
E09000025	Newham	UK	24.7
IT306	Marcianise	IT	24.8
E09000002	Barking and Dagenham	UK	24.9
E09000028	Southwark	UK	25.2
E09000013	Hammersmith and Fulham	UK	26.0
E06000021	Stoke-on-Trent	UK	26.0
E09000022	Lambeth	UK	26.2
E08000012	Liverpool	UK	26.4
E08000003	Manchester	UK	26.5
E09000023	Lewisham	UK	26.7
E09000012	Hackney	UK	26.7
E08000023	South Tyneside	UK	26.8
NLGM0363	Amsterdam	NL	27.0
S12000046	Glasgow City + South Lanarkshire	UK	27.0
FR163	Lens	FR	27.1

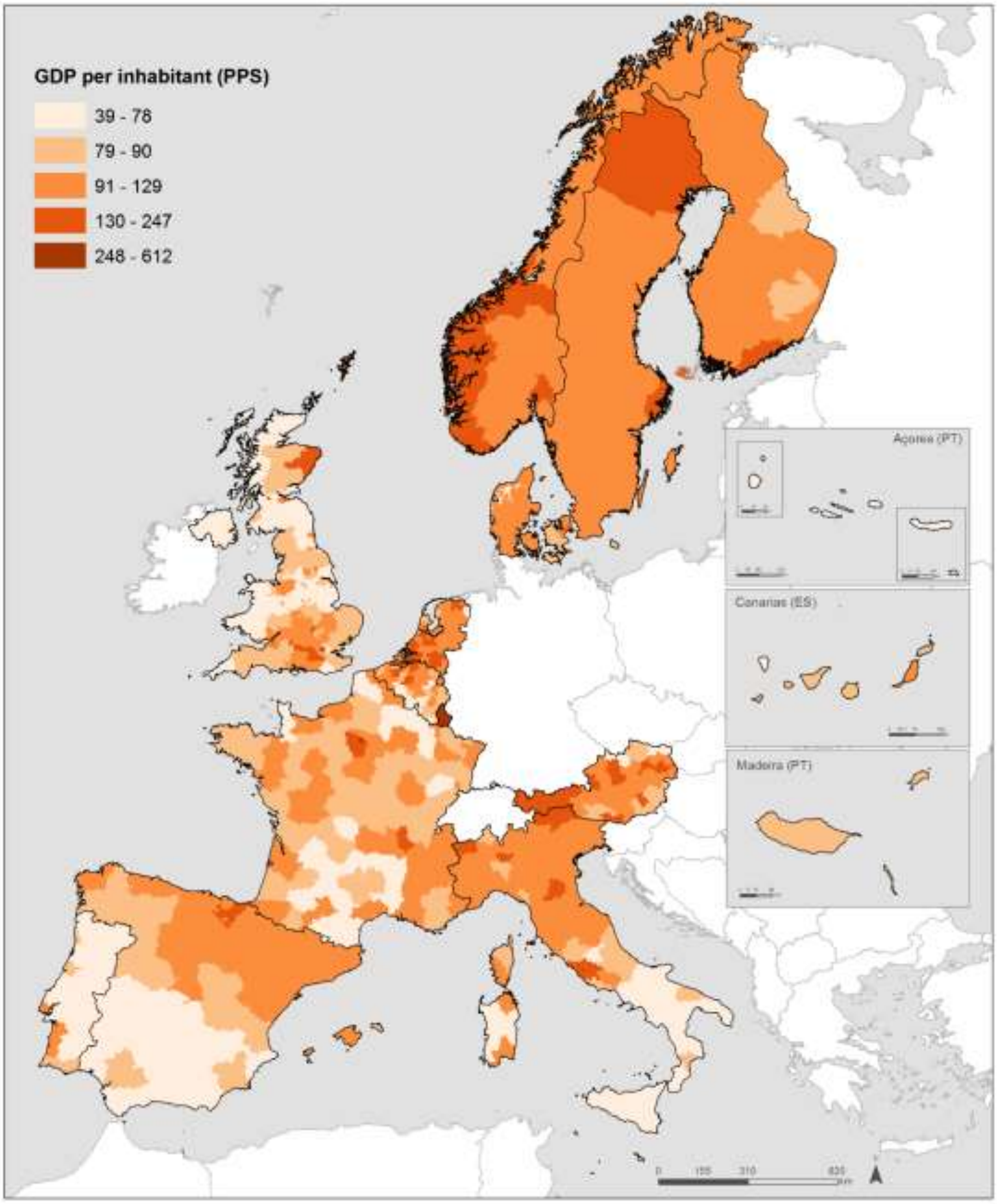
HIGH SURVIVAL			
GEOCODE	NAME	COUNTRY	SURVIVAL RATE
FR129	Florac	FR	49.6
ES142	Guadarrama	ES	49.5
FR295	Strasbourg-Ville	FR	47.9
PT510	Vila de Rei	PT	47.6
ES63	Campiña (Guadalajara)	ES	47.5
ES300	Sur Occidental (Madrid)	ES	47.2
AND81	Encamp	AD	46.6
ES296	Soria	ES	46.5
FR266	Sainte-Menehould	FR	46.3
FR228	Palaiseau	FR	46.0

GEOCODE	NAME	COUNTRY	SURVIVAL RATE
ES130	Fuerteventura	ES	45.7
FR246	Rambouillet	FR	45.7
FR26	Auch	FR	45.6
ES174	Lozoya Somosierra	ES	45.3
ES264	Sayago	ES	45.2
FR185	Mayenne	FR	44.6
FR326	Vire	FR	44.3
ES261	Salamanca	ES	44.1
FR4	Ajaccio	FR	44.1
ES5	Alcarria Alta	ES	44.1
ES40	Baix Penedès	ES	44.0
FR254	Rochechouart	FR	43.7
CH7	Meilen	CH	43.7
ES64	Campiña (Madrid)	ES	43.6
FR181	Mantes-la-Jolie	FR	43.6
BE360	Woluwe-Saint-Pierre	BE	43.6
ES245	Ribera	ES	43.6
ES309	Tierras de León	ES	43.5
FR206	Mortagne-au-Perche	FR	43.4
FR174	Louhans	FR	43.4
FR120	Draguignan	FR	43.4
FR220	Niort	FR	43.2
ES50	Benavente y Los Valles	ES	43.2
FR232	Pau	FR	43.1
FR7	Alençon	FR	43.0
E07000077	Uttlesford	UK	42.9
FR17	Antony	FR	42.9
FR85	Chartres	FR	42.5
ES266	Segovia	ES	42.5
FR249	Rennes	FR	42.5
FR78	Castres	FR	42.5
ES88	Central (Lugo)	ES	42.4
FR66	Brignoles	FR	42.4
ES256	Rioja Media	ES	42.2
ES258	Sagra-Toledo	ES	41.9
ES28	Arlanzón	ES	41.9
FR3	Aix-en-Provence	FR	41.5
FR177	Lyon	FR	41.2
FR139	Grasse	FR	41.1

Where do people live longer and shorter lives? An ecological study of old-age survival across 4404 small areas from 18 European countries.

Appendix 7

Supplementary material 4. Regional gross domestic Product (GDP) per inhabitant, in purchasing power standards (PPS) by NUTS 3, 2011.



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Appendix 8

Additional material 1: Georeferencing of crime records

Georeferencing of crime records took three steps:

1) Standardization of street names and correction of spelling errors;
2) Georeferencing of crime records either in the rooftop of the building (when the complete address was available), in the centroid of the street segment (when the door number interval of the street segment of occurrence was available) or in the centroid of the street (when the name of the street of occurrence was the only information available)
3) Counting of crime frequency (by category) in each location;

Because we needed a measure of crime for each census tract (i.e. neighborhood) the following procedures were required:

4) Creation of a buffer of 100 meters around each crime location and intersection with census tract (for which we had population data) to assess the population within each buffer.
5) Computation of crime rates in each buffer as following:
$$\frac{total\ crimes\ within\ the\ buffer}{population\ within\ the\ buffer} \times 1000$$
6) Because frequently more than one buffer intersected with each census tract, we choose to attribute to the census tract the highest crime rate of the buffers that intersect it.

Distance to parks and non-residential destinations influences physical activity of older people, but crime doesn't: a cross-sectional study in a southern European city

Appendix 9

Additional material 2: Categorization of crime records

Category	Description	Crime	
Traffic (n=2,270)	Crimes associated with the violation of traffic rules and road safety.	• Driving under the influence (1211) • Unlicensed driving (1015) • Reckless or dangerous driving (36)	• Assault in traffic accident (7) • Homicide in traffic accident (1)
Incivilities (n=492)	Mild forms of misbehavior as public drunkenness, delinquent behavior and situations that cause disorder and sense of public insecurity.	• Drug traffic (354) • Possession or traffic of prohibited weapons (64) • Other offenses related to drugs (60)	• Heritage damage (3) • Drug possession (10) • Child possession and prostitution (1)
Criminal offenses without violence (n=8,922)	Menacing crimes without victim approach	• Theft in motor vehicle (3,122) • Theft in residence with burglary, scaling or false keys (1404) • Theft by pickpocket (967) • Theft of motor vehicle (913) • Other thefts (774) • Theft in commercial or industrial building with burglary, scaling or false keys (676) • Threat or coercion (577) • Theft in supermarket (173)	• Coercion-resistance of worker (120) • Theft in other buildings, with burglary, scaling or false keys (89) • Theft in the school, with burglary, scaling or false keys (63) • Burglary (38) • Theft and traffic of art and culture (3) • Child abduction (2) • Human traffic (1)
Criminal offenses with violence (n=4,034)	Menacing crimes with victim approach	• Simple assault (1200) • Domestic violence against partner (1125) • Robbery in the street (787) • Other domestic violence offenses (375) • Theft/pickpocketing (302) • Other robbery (141) • Aggravated assault (29) • Domestic violence against minors (23) • Robbery of public transport driver (13)	• Taking, confinement, or restrain (8) • Intetional homicide (7) • Child abuse (6) • Rape (6) • Child sexual abuse (5) • Other assault offemses (4) • Bank robbery (2) • Service station robbery (1)

Long-lived lives - The role of the contextual determinants

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